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AN ILLUMINATING TOOL FOR VEHICLE DESIGN

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SUMMARY

Water facilities play a fundamental role in the design of air, ground, and marine vehicles by providing a qualitative, and sometimes quantitative, description of complex flow phenomena. Water tunnels, channels, and tow tanks used as flow-diagnostic tools have experienced a renaissance in recent years in response to the increased complexity of designs suitable for advanced technology vehicles. These vehicles are frequently characterized by large regions of steady and unsteady three-dimensional flow separation and ensuing vortical flows. The visualization and interpretation of the complicated fluid motions about isolated vehicle components and complete configurations in a time- and cost-effective manner in hydrodynamic test facilities is a key element in the development of flow control concepts and, hence, improved vehicle designs.

This paper presents a historical perspective of the role of water facilities in the vehicle design process. The application of water facilities to specific aerodynamic and hydrodynamic flow problems is discussed, and the strengths and limitations of these important experimental tools are emphasized.

1. INTRODUCTION

The successful development of vehicles suitable for aerodynamic and hydrodynamic applications requires an understanding of the configuration flow field at design and off-design conditions. Water facilities (tunnels, channels, and tow tanks) have historically provided valuable information on the fundamental fluid mechanics of two-dimensional (2-D) and three-dimensional (3-D) aerodynamic and hydrodynamic shapes operating at low speeds. The application of hydrodynamic facilities to basic aerodynamic research problems that was pioneered by Ludwig Prantl in the early days of flight continues to the present day. The advent of high-performance flight vehicles that incorporate flow separation by design has promoted a surge of interest in water facilities as a diagnostic tool. The utilization of water tunnels, channels, and tow tanks to visualize the 3-D separated and vortical flow fields about advanced, highly swept, military aircraft and slender missile configurations operating at extreme attitudes (angles of attack and sideslip) has been demonstrated by many researchers. The increased level of confidence attained by correlating study results with aerodynamic facility and flight results has led to a substantial increase in the applications of relatively simple water facilities to the complex aerodynamic and hydrodynamic shapes of interest for present- and future-generation vehicles. Concurrently, flow visualization and nonintrusive measurement techniques have been developed, modified, and implemented to provide qualitative and quantitative information on the steady and unsteady flow fields about isolated vehicle components and complete configurations. In general, the use of hydrodynamic facilities has risen in direct proportion to the advancement of air, ground, and marine vehicle technologies. As a consequence, water facilities are now an important element in the design process, yielding insight into the complicated vortical fluid mechanisms and structures that are characteristic of flows about advanced-technology vehicles.

The visualization of a flow phenomenon represents a major advancement toward understanding and, subsequently, controlling the fluid mechanism. Flow visualization is easily performed in water and, as a consequence, aerodynamic as well as hydrodynamic problems have long been studied in water facilities. The flow properties of water are similar to those in air, provided the flow simulations are restricted to the incompressible regime. The selection of water as a flow-visualization medium is largely based on the 800-fold increase in the density relative to air and, consequently, the excellent light-reflecting characteristics of tracers injected into the flow field. Suitable illumination of the tracer particles (aluminum powder, dye, or hydrogen bubbles, for example) provides direct visualization of steady and unsteady flows. At the same scale and speed, the Reynolds number is 15 times greater in water than in air. However, cost, complexity, and facility space are factors that constrain the test section size; hence, the model scale is generally relatively small. In addition, the fluid velocities are typically less then 10 ft/sec in order to preserve the clarity of the flow structure, to avoid excessive model loads, and to preclude cavitation when it is an undesired phenomenon. The combination of small model scale and low fluid velocities results in Reynolds numbers that are orders of magnitude less than those achievable on larger-scale models in wind tunnels or on full-scale air, ground, and marine vehicles operating in their respective environments. As a consequence of this Reynolds number mismatch, the fluid motion under

consideration must be the kind that is insensitive to changes in the Reynolds number. At the least, the fundamental structure of the flow must be similar, regardless of the Reynolds number. It is fortunate that many of the complex flow phenomena, particularly 3-D motions with vortices or predominantly separated regimes, associated with advanced-technology vehicles, lend themselves to qualitative (and sometimes quantitative) evaluation in these facilities. The interpretation and application of the results obtained in water tunnels, channels, and towing tanks at low Reynolds numbers are topics of considerable debate in the technical community. This meeting is both timely and useful as it provides a forum for the discussion of the strengths and limitations of hydrodynamic test facilities applied to flow problems in aeronautical and maritime fluid dynamics.

Section 2 of this paper will present a historical review of water facilities. Because of the large number of water facilities that have been in operation over the years and that remain in operation today, the discussion will center on representative facilities. The applications of water facilities to vehicle design, encompassing the interests of the various sessions of this meeting, are discussed in Section 3. Of necessity, only the flavor of the myriad basic and applied aerodynamic and related hydrodynamic studies will be provided to demonstrate the utility and current potential of water facilities.

2. HISTORICAL PERSPECTIVE

2.1 From Antiquity to the Renaissance

The visualization of complex flow phenomena in a water medium spans millennia. Observations and speculations on vortical flows in nature go back to prehistoric times (Ref. 1). Stone Age artifacts depicted the spiral motions that were frequently observed in a water medium. Over 2,000 years ago, the writings of Aristotle (384-322 B.C.) described the observations of whirlpools at sea and the resultant loss of ships caught in this powerful fluid motion (Ref. 1). Von Karman (Ref. 2) wrote of an early painting in Bologna, Italy, of St. Christopher walking through a flowing stream that showed alternating vortices, or Karman "vortex streets," behind the saint's foot. In the centuries to follow, the nonscientific observations of flows in water persisted.

The earliest documentation of flow mechanisms in water for scientific purposes appears to be in the writings and elaborate drawings of Leonardo da Vinci (1452-1519) (Ref. 3). As pointed out by Lugt (Ref. 1), Leonardo's artistic descriptions of nature single out a particular phenomenon, such as a vortex, from a global flow field and are, therefore, in common with scientific experiment. Examples of his fluid flow sketches are shown in Fig. 1 taken from Ref. 1. Leonardo frequently discussed the similarity of fluid motions in water and air. According to the account of Truesdell (Ref. 4), such a conclusion could come only from direct observation of the fluid motions in both media. In fact, Leonardo was the first to discuss water and air as fluids, and he designed the first water tunnel flow-visualization facility as shown in Fig. 2 (from Ref. 5). Leonardo also recognized the limitations of simulations of airflow in a water medium due to the effects of compressibility.

2.2 From 1600 to 1800

A century after Leonardo's passing, Sir Isaac Newton (1642-1727) claimed that his so-called "sine-square law of air resistance" applied as well to water, where the forces were proportional to the respective densities (Ref. 2). Newton's statement was noteworthy in that it promoted the application of experimental results in water to motion in air and vice versa. Newton's influence was present in the experiment of Edme Mariotte (1620-1684), who measured the force acting on a flat plate submerged in a stream of water. Jean Charles de Borda (1733-1799) performed experiments in a water facility using bodies of various shapes, which were put in motion by means of a rotating, or whirling, arm. Jean Le Rond d'Alembert (1717-1783), Antoine Condorcet (1743-1794), and Charles Bossut (1730-1814) towed ship models in still water (see Ref. 2). These investigations represented perhaps the first application of the towing-tank technique that is so prevalent today. In 1780, J. C. Wilke used a water facility to study atmospheric vortices (Ref. 1).

2.3 From 1800 to 1900

Sporadic experiments using water as the working fluid continued into the 19th century. In 1839, Hagen (Ref. 6) conducted studies of water flowing through cylindrical tubes, where he observed the transition from laminar to turbulent flow. Hagen subsequently conducted more detailed testing of flow stability in tubes and documented his results in 1854 (Ref. 7). In 1883, Osborne Reynolds conducted his classic experiments (Ref. 8) in which he demonstrated that flow transition occurred when a parameter, now called the Reynolds number, exceeded a certain value. His flow-visualization results were documented by sketches rather than photographs. Interestingly, Reynolds' experiments were repeated nearly 100 years later in his original apparatus at the University of Manchester and representative results are documented by Van Dyke (Ref. 9). In 1897, Hele Shaw performed experiments (Ref. 10) in a thin tank to study 2-D highly-viscous flows. The experiments of researchers spanning four centuries, starting with the work of Leonardo, contributed to the development of new flow-visualization facilities and techniques which led to major advances in fluid mechanics.

2.4 From 1900 to 1935

The utilization of water facilities as tools to study a wide range of fundamental aerodynamic and hydrodynamic problems was pioneered by Ludwig Prandtl in Germany beginning in the early 1900s. Prandtl conducted experiments on 2-D shapes in a water channel where the flow was visualized on the free surface using aluminum powder. His flow-visualization method was first documented in 1904 in Ref. 11. A compilation of Prandtl's 2-D flow-visualization results obtained at the Kaiser Wilhelm Institute (KWI) for Flow Research in Göttingen, Germany was provided by Prandtl and Tietjens (Ref. 12) in 1934. His studies included (1) the propagation of turbulence in boundary layers, (2) vortex shedding downstream of a plate, (3) vortex development behind a nonrotating cylinder and the development of Karman vortices, (4) laminar and turbulent boundary layers, (5) flow development around a rotating cylinder, (6) starting vortex generated by an airfoil, (7) flow in a diffuser with and without suction at the walls, and (8) cavitation phenomena. Examples of Prandtl's results are shown in Fig. 3 (from Ref. 12). The advancement of fluid mechanics through the use of a water facility and the intuitiveness of the experimenter is exemplified by item (3) above. Karl Hiemenz, a student of Prandtl, built a water channel in 1911 to observe the flow separation behind a cylinder. The oscillatory vortex shedding that he observed was unexpected and the phenomenon was at first attributed to model and tunnel wall asymmetries. The flow situation was always repeatable, however, despite careful checks of the model and test facility. This attracted the attention of von Karman (Ref. 2) who speculated that there may be a natural and intrinsic reason for the phenomenon. He calculated the stability of such a system of vortices, which led to the understanding of the now-famous Karman "vortex street."

The efforts of Prandtl and his colleagues confirmed that, under certain conditions, the flow patterns in the vicinity of a body are similar in air, water, or other liquid or gaseous fluids. On this basis, Prandtl demonstrated that the fluid dynamic characteristics of a body exposed to a flow in one medium could be predicted from experiments in a different medium. Prandtl's work overlapped the development of flight vehicles for military and commercial applications, and airplane wings were, accordingly, investigated in hydrodynamic facilities. It is noted that hydrodynamic can refer to imcompressible flow characteristics in any fluid, including air at low Mach numbers. Since the practical design of aircraft did not seriously account for compressibility during the first 20-30 years of its history because of the low flight speeds, water facilities were applied to flight-vehicle design, albeit on a limited basis.

From approximately 1910 to 1935 the majority of water-facility investigations of aerodynamic flow problems were of a 2-D nature and emphasized the boundary-layer behavior and flow-separation characteristics of airfoil shapes suitable for the relatively unswept wings of this period. The KWI in Göttingen, Germany, maintained its role as a leader in the study of laminar and turbulent boundary layers and the drag of aerodynamic shapes (Ref. 12). More frequently, however, water channel facilities were employed for hydrodynamic flow problems relating to cavitation phenomena and the resistance of surface ships and submersibles. Hoerner (Ref. 13) provides an extensive list of references of water tunnel, channel, and towing-tank investigations of marine vehicles conducted during this period.

2.5 From 1935 to 1950

The contributions of water facilities to vehicle design increased during the period 1935-1950, largely because of the global political climate that would lead to World War II and the ensuing demands for military air and sea superiority. The water facilities in Göttingen were used by the German aircraft industry to improve the design of propeller and jet aircraft during World War II. Reichardt (Ref. 14) described the results of hydrodynamic tests to develop efficient low-speed aerodynamic shapes using a cavitation method. The basis of this study was that gaseous flows at sonic speed had a certain resemblance to fluid motions at cavitation. The test models were streamlined in the water tunnel to delay cavitation onset. The resultant shapes provided a rough approximation of the desired geometries in air that would exhibit delayed onset of locally sonic flow on the surface. The nacelles, nacelle-wing fairing, and wing-body transition on the Me 262 were modified in this manner. The Germans also utilized a water facility to aid in the development of marine vehicles. An advanced submarine type "XXI" was developed, in part, from towing-tank investigations (Ref. 13). The test results led to a hull having a continuous shape, a streamlined conning tower, and guns integrated into the tower.

The Allies also used water facilities during World War II for the improved design of marine and flight vehicles. Notable water tunnel, channel, and towing-tank facilities were located at the National Physical Laboratory (NPL) and Admiralty Research Laboratory (ARL) in England and at the California Institute of Technology (CalTech), National Advisory Committee for Aeronautics (NACA), and David Taylor Model Basin (DTMB) in the United States. The majority of water facility applications to vehicle design during this period pertained to marine craft. Typical studies in these facilities addressed the cavitation phenomena associated with ship propellers and hydrofoils (ship rudders and submarine planes, for example) and the drag/resistance of hydrofoils, displacement hulls, submersibles, torpedoes, surface-piercing struts, seaplane floats/skis, and planing craft (Ref. 13). Hydrodynamic problems that were addressed and solved in water facilities included that of submarine periscope vibration, associated with periodic vortex shedding; this problem was alleviated by means of guidevanes. The reduction of missile drag at water entry was achieved by improved nose shapes developed from water-facility testing (Ref. 13). A parametric study of the flow separation characteristics of projectiles having various forebody and afterbody shapes and fin arrangements was performed in 1944 by Knapp (Ref. 15) in the CalTech High Speed Water Tunnel. The detailed flow-field observations from this study were intended to aid the projectile and bomb designers during the latter stages of the war. Aircraft wings were still relatively

unswept and of high aspect ratio. As a consequence, airfoils were generally tested, and the results were corrected for 3-D effects.

A common problem was manifested in the experimental investigations of marine and flight vehicles during this period, namely, how to transfer the model results to full-scale operation. The limited dimensions and flow speeds of water tunnel, channel, and towing-tank installations generally resulted in Reynolds numbers in model testing that were typically two to three orders of magnitude less than those of the full-scale operation. For example, the drag of displacement hulls consisted of two predominant components, skin friction and wave resistance, that were governed by different similarity laws. Unless full-scale dimensions were used, it was not possible to simulate correctly the full-scale conditions in towing tanks. It became common practice, then, to satisfy the dynamic similarity (Froude number), producing the proper wave pattern, and to correct the skin-friction component on the basis of the Reynolds number. The Reynolds number could be increased by heating the water. However, the disparity between model- and full-scale conditions was still large. The scaling of cavitation phenomena observed in water-facility testing of ship propellers and hydrofoils was a persistent challenge, particularly under conditions of incipient and fully developed cavitation.

The introduction of jet-powered aircraft toward the end of World War II and the ensuing emphasis on high-speed flight posed particular problems for water-facility simulations owing to the significant Reynolds number gap and the effects of compressibility (Mach number). Operation of water facilities at higher speeds resulted in undesired cavitation phenomena that restricted the speed up to which a flow pattern in water could be expected to represent that around the same shape in air. Cavitation could occur within the fluid at some distance from the model surface, in the cores of vortices from aircraft propeller blade tips or in the separated flow past blunt or bluff bodies, for example, which precluded the correlation of the water-facility data to the conditions in air. Closed-section facilities could be pressurized to delay cavitation onset; however, this was done at increased facility complexity and cost. As a result of these considerations, constraints were necessarily imposed on the use of water facilities as a design tool, particularly with regard to flight vehicles.

2.6 From 1950 to 1960

The work of German researchers during World War II and of R. T. Jones in the United States during the same period led to wing sweep as a means of delaying transonic flow effects (see Ref. 2). The fluid mechanics associated with these wings was not well-understood owing to the 3-D nature of the flow. At off-design conditions, the swept separation lines and ensuing vortices were important features of the 3-D flow field. The early 1950s also marked the advent of first-generation supersonic transport (SST) aircraft featuring thin, slender wings. By design, the configurations utilized leading-edge vortex-induced lift for improved takeoff and landing performance. This was a significant departure from the time-honored attached-flow wing designs.

The complexity of the wing vortical flow field and the associated aerodynamic nonlinearities were demonstrated in the late 1940s and early 1950s by researchers in England, France, the United States, Canada, and Sweden (Refs. 16-20, for example). These experimental investigations underscored the need for a flow-visualization tool in order to understand and control the powerful fluid motions. The early studies suggested that once flow separation occurred everywhere along the leading edge of a swept wing, the fundamental character of the vortex was insensitive to the Reynolds number (Ref. 21). The vortex flow structure also remained much the same over a wide range of the Mach number (Ref. 22), provided the wing leading edge was swept within the Mach cone and shock waves did not interact with the vortices. A new era of water-facility applications to aircraft design therefore emerged and was characterized by extensive testing of slender wings suitable for commercial and military aircraft configurations with a requirement for supersonic operation.

The principal advocates of water-facility applications to air-vehicle design in the 1950s included the NPL in England, the Office National d'Etudes et de Recherches Aérospatiales (ONERA) in France, the National Aeronautical Establishment (NAE) in Canada, the NACA and CalTech in the United States, and Kungl Tekniska Högskolan (KTH) in Sweden. The pump-driven horizontal water tunnels at the NPL and NAE, the vertical water tunnel at ONERA operating by gravity discharge, the towing tank at the NACA, the free-surface water channel and pressurized high-speed water tunnel at CalTech, and the water tank at the KTH represented several different facility designs that were used for a common purpose, namely, to develop a flow-visualization data base on aircraft and aircraft-related configurations. The clarity of the flow visualization from experiments conducted in these installations established water facilities as a useful diagnostic tool to study the flow about 3-D aerodynamic shapes operating within an expanded flight envelope. For example, the water tunnels at the NPL and ONERA contributed to the understanding of the controlled flow separations and vortical motions on the SST Concorde developed jointly by the English and the French. The water tank at the KTH was utilized in Sweden's pioneering studies of canard-wing aircraft. The water tunnel at the NAE deserves special note owing to its colorful history. The facility was built at the Aerodynamische Versuchsantalt in 1939 in Göttingen, Germany, and, subsequently, was shipped to Canada after World War II (Ref. 23). One of the early investigations conducted at the NAE was related to the design of cockpit canopy shapes for the CF-100 and CF-103 aircraft by generating a cavitation bubble whose shape conformed to the constant-pressure contour (Ref. 24). This experimental approach was similar to Reichardt's (Ref. 14), whose work in Germany was discussed earlier. An undocumented study was performed of the lateral instability caused by asymmetric breakdown of wing leading-edge vortices. This subject remains of great interest to modern-day fighter aircraft configurations. The NAE facility was

also utilized to study the effects of the exhaust from jet-powered aircraft on the flow about tail surfaces.

Water facilities maintained their role in the marine-vehicle design process in the post-World War II years. Major contributions to the design of surface ships, submersibles, and marine propulsion systems were made by researchers in many countries. Primary contributors to marine vehicle technology included the NACA, DTMB, Iowa Institute of Hydraulic Research, St. Anthony Falls Hydraulic Laboratory (University of Minnesota), and CalTech in the United States; the Ship Model Basin in the Netherlands; the Supramar company in Switzerland; and the State Shipbuilding in Sweden. Reference 25 lists many of the research installations involved in maritime testing during this period. An upsurge in the use of hydrofoil craft began in the late 1950s. As noted by Acosta (Ref. 26), the successful achievements of hydrofoil craft and the possibility of high speeds at sea were due to the greatly increased understanding of the flow past hydrofoils. In a manner similar to the field of aeronautics, water facilities played a key role in the advancement of hydrofoil technology.

2.7 From 1960 to 1970

Numerous slender-wing aircraft configurations emerged during the 1960s that were characterized by leading-edge vortex formation at off-design conditions. These aircraft included the F-111, YF-12, and XB-70 in the United States; the Mirage III and IV in France; the HP-115 experimental aircraft in England; the Concorde in a joint English/French effort; and the Viggen in Sweden. In addition, the design of highly maneuverable transonic fighter aircraft began during this period in the United States, and this work would culminate in the F-16 and F-18 fighters in the 1970s. From the outset, these designs employed wing-body strakes or leading-edge extensions (LEXes) to generate concentrated vortices for enhanced lift at takeoff and landing and at subsonic/transonic maneuvering conditions.

The water tunnels at the NPL in England, ONERA in France, and NAE in Canada continued to be utilized successfully in the study of slender-wing vortices. A copy of the NPL tunnel was built at the University of Southhampton, England, and static and dynamic testing of slender-wing vortex flows was performed (Ref. 27). Excellent correlations were obtained by Werlé (Ref. 28) at ONERA of the vortex behavior on delta wings and specific aircraft configurations such as the Concorde and the Douglas F-5D (Ref. 29) in water tunnels, wind tunnels, and flight. These results established confidence that, for the special case of leading-edge vortices on thin, highly swept surfaces, water facilities could be used as a diagnostic tool despite the Reynolds number gap. ONERA assembled a laboratory consisting of two vertical water tunnels and a water tank that was dedicated to the study of aerodynamic and hydrodynamic flow phenomena. The French were at the forefront of flow-visualization technology and they applied water facilities to a wide range of aerodynamic flow situations. These included laminar and turbulent boundary layers, boundary-layer separation on 2-D and 3-D shapes, vortex-dominated flows on slender bodies and wings, jet mixing and interaction phenomena, blowing for boundary-layer control, vortex enhancement by spanwise blowing, ground effects on the flow about the Concorde using a moving ground board, models with internal flows (engine intakes, for example), and a helicopter rotor in translation and hover (Ref. 30). The ONERA laboratory became the standard of excellence in flow visualization and was the forebearer of numerous other water facilities throughout the world.

The NAE water tunnel was a consistent source of useful flow-field information on complex flow phenomena in the 1960s. The 3-D separated flow-characteristics about numerous aerodynamic shapes were investigated. The circulation-control concept for enhanced, high-lift aerodynamics was studied on round airfoils, flaps, etc. Other experiments featured lifting propellers at high angles of inclination, ducted fans, and fan-in-wing arrangements. The wing-submerged lifting-fan investigations were indicative of the increased sophistication of water-facility experiments of aircraft models and of the information gained from these studies. In this case, the fan-airfoil interactions and wing-fan efflux interactions were observed in order to assess the flow effects leading to changes in the configuration forces and moments.

The heavy commercial and military transport aircraft that appeared during this period generated powerful trailing vortex systems that posed a flight safety hazard to trailing aircraft. Water towing-tank facilities were well suited to study the vortex patterns and methods of wake alleviation, and the National Aeronautics and Space Administration (NASA), the Douglas Aircraft Company, and the Lockheed-Georgia Company in the United States employed such facilities for this purpose. The NAE conducted water tunnel experiments of the vortex flows shed from upswept rear fuselages similar to those of rear-loading aircraft. The vortices were found to promote adverse effects on the pitch stability and cruise drag and to produce undesirable loadings on rear cargo doors (Ref. 31).

2.8 From 1970 to 1980

Vehicle designers in the 1970s were once again confronted with a large experimental data gap caused by the emerging requirement for advanced tactical missile and fighter aircraft configurations to operate in a controlled manner at extreme attitudes. The vortex-dominated flows shed from the slender bodies and wings of highly maneuverable flight vehicles were not well understood. The flow-visualization and flow-measurement techniques in wind tunnels and in flight were inadequate for the detailed definition of the highly 3-D flow fields that were often characterized by multiple vortex development, vortex interactions, and vortex breakdown. As a consequence, the 1970s marked a significant upsurge in the use of water facilities in the vehicle design process.

To improve the understanding of the structure of vortex core breakdown, experiments were conducted by Sarpkaya in the United States using a water facility (Ref. 32). Water to which swirl was imparted by upstream vanes flowed through a slightly divergent tube and the forms of vortex bursting were observed. The experimental results also supported the development of computational methods to predict vortex core instabilities.

Water tunnels, channels, and towing tanks were in operation in many countries, and studies in support of vehicle design were performed in the United States, Canada, France, England, Belgium, Germany, Switzerland, the Netherlands, Sweden, Russia, Australia, Japan, and China. The confidence in water facilities as a flow-diagnostic tool was reflected by the diversity of research subjects encompassing air, ground, and marine vehicles.

A leader in the application of water tunnels to the simulation of fighter aircraft flow fields at high angles of attack was Northrop Corporation in the United States. Influenced in large part by the work of Werlé (ONERA) in France, M. S. Cahn and G. R. Hall led the effort at Northrop in the mid-1970s to develop a water facility that would augment the aircraft design process (Ref. 33). An early application of a small pilot tunnel modeled after the ONERA gravity-discharge facility was the visualization of the LEX vortex flows on a small-scale model of the Northrop YF-17 lightweight fighter configuration. The vivid definition of the YF-17 vortical flows stimulated sufficient support to construct a larger water tunnel that is still in operation today. This facility was used extensively in all of the military aircraft programs at Northrop to understand and control the forebody and wing vortex flows, vortex interactions and breakdown, and vortex-empennage interactions. Models of virtually every fighter aircraft in the United States inventory and of numerous foreign military aircraft configurations were tested in the Northrop installation. The role of this tunnel rapidly expanded to include the study of 2-D nozzle exhaust effects on afterbody flow separation, nozzle exhaust plumes and jet mixing processes, forebody and wing vortex control by active and passive means, hot-gas reingestion phenomena on V/STOL aircraft in ground proximity, vortex flow management for improved performance of top-mounted inlets, thrust reverser plume trajectories and the effects on wing and tail flow fields, the structure of swirling jets, self-induced lateral oscillations (wing rock) of slender planforms, deflected wing leading- and trailing-edge flap effects on vortex stability, oscillating wing control surfaces for flow control, vortex shedding on an aircraft model in a flat spin, and canard-wing, forward-swept wing, and oblique wing flow fields (Ref. 34).

ONERA in France and the NAE in Canada continued to excel in their high-quality and diverse applications of water facilities to vehicle design. The confidence gained from years of experience in hydrodynamic testing led to the use of the ONERA and NAE facilities to study ground vehicle configurations such as high-speed trains, trucks, automobiles, and snowmobiles. The water facilities were used to identify regions of 3-D flow separation and to develop aerodynamic "fixes" to improve the vehicle performance. Marine vehicle investigations were also undertaken in these tunnels to study the separated flow fields about the superstructure of surface ships and highly maneuverable submarines. The trend toward high-performance air, ground, and marine vehicles facilitated the acceptance of water facilities as a design tool, owing to the complicated fluid motions that were often vortex-dominated.

The French and Canadians were leaders in the investigation of unsteady vortical motions. The ONERA installation was utilized to study the vortex formation on the upper surface of an oscillating profile, which simulated the cyclic variation in pitch of a helicopter rotor blade (Ref. 30). In addition, the vortex-shedding characteristics of a spinning fighter model were investigated. The NAE performed forced oscillation testing of a modern aircraft configuration to identify the effects of the body vortices on the static and dynamic cross derivatives (Ref. 35).

Interest in the unsteady aerodynamics of helicopter rotor blades led to numerous investigations of the dynamic stall behavior of oscillating airfoils (Ref. 36) at the U.S. Army Research and Technology Laboratories (AVRADCOM) at NASA Ames Research Center. A unique feature of the water tunnel experiments was the measurement of the force and moment time histories in combination with vivid off-body flow visualization.

The Flow Research Company towing tank and the Tracor Hydronautics Ship Model Basin in the United States emerged as important water facilities for aerodynamic flow simulations. The Flow Research facility was used in the general research of unsteady aerodynamics; separated flows; and laminar, transitional, and turbulent boundary layers. The Tracor model basin was used extensively by NASA for measurements of the trailing vortex systems generated by models of wide-body commercial transport aircraft such as the Boeing 747.

The continued interest in V/STOL aircraft prompted the development of water facilities at Rockwell International (Ref. 37) and the McDonnell-Douglas Corporation (Ref. 38). These were dedicated to the visualization of ground-effect phenomena associated with multijet arrangements.

The U.S. Air Force Wright Aeronautical Laboratories (AFWAL) constructed a small water tunnel operating by gravity discharge. This facility proved useful in visualizing the vortex flows about advanced fighter models, including several forward-swept-wing configurations.

Water facilities also experienced a renaissance in the European government, industry, and university communities. The towing tank at Deutsche Forschungs- und Versuchsanstalt für Luft- und Raumfahrt (DFVLR) in Göttingen, Germany, was applied to the study of wing leading-edge vortices (Ref. 39). A water tunnel

built at Messerschmitt-Bölkow-Blohm (MBB) in Munich, Germany, became a useful aid in recognizing and solving flow problems during the aircraft development phase (Refs. 40 and 41). The University of Stuttgart, with a history of water facility experience dating back to 1950, continued its fundamental fluid mechanics research. The behavior of slender missile vortices at extreme attitudes was investigated in a water tunnel at the British Aerospace Military Aircraft Division (Ref. 42). A study of the Reynolds number sensitivity of delta wing vortex breakdown was performed in a water tunnel by Svenska Aeroplan Aktiebolaget (SAAB) in Sweden (Ref. 43). Leading-edge vortex flow studies were also conducted in a water facility at the von Karman Institute (VKI) in Belgium (Ref. 44). The Netherlands Ship Model Basin maintained a leadership role in hydrodynamic testing of displacement hulls and marine propulsion systems.

The Aeronautical Research Laboratories (ARL) of the Australian Department of Defence conducted systematic experiments of vortex flows in the mid-1970s using water towing tank and water tunnel installations. The trailing-vortex system generated by a rectangular planform wing was investigated in the towing tank and the experimental trends pertaining to the vortex structure and dissipation were in qualitative agreement with available wind tunnel and flight test results (Ref. 45). The structure and breakdown of the leading-edge vortices shed from slender delta and cranked wing planforms were observed in the water tunnel (Ref. 46).

2.9 From 1980 to the Present

Water facilities have gained general acceptance throughout the world as valuable diagnostic tools to aid in the vehicle design process. The unique ability of these installations to visualize 3-D vortical motions about complicated aerodynamic and hydrodynamic shapes has been utilized in vehicle development programs in several countries. Vortical flows have become a "way of life" on all classes of vehicles as shown in the sketches in Fig. 4 (from Ref. 1). The emphasis on low-observable flight vehicles has led to aerodynamic shapes that are dominated by vortex flows. Clearly, the identification and control of these 3-D separated regimes is an important element in air, ground, and marine vehicle performance optimization.

The sophistication of water facilities and flow visualization and measurement techniques has increased in concert with the advancement in vehicle technology. In addition to the qualitative information gained from water-flow experiments, efforts are now under way to extract more quantitative data than previously possible. As indicated by Gad-el-Hak (Ref. 47), the advent of advanced computers capable of handling high-resolution images has made it possible to combine flow-visualization and digital-image processing techniques to obtain quantitative information. Lasers have become a key element in many water facility installations. Quantitative flow-field information has been obtained in recent water-flow experiments of vortical motions using 2-D laser velocimetry (Ref. 48). Laser optics have also been used to generate an intense sheet of light to enhance the visualization of the flow structure in arbitrary planes (Ref. 49). A laser-induced fluorescence visualization technique can provide more detailed information on the structure of complex flows (Ref. 50). The interest in unsteady aerodynamics has led to more sophisticated model support apparatus and instrumented models.

The water facility "standard bearers" of the 1970s continue to make major contributions in this decade to the understanding and control of the flow about advanced vehicles. In recent years, emphasis at Northrop has been placed on the establishment of a flow visualization data base on present- and future-generation fighter aircraft configurations that are characterized by highly coupled forebody and wing vortex systems at extreme attitudes (see Ref. 51). ONERA in France and the NAE in Canada continue a long-standing tradition of excellence in water facility applications to air, ground, and marine vehicle design (Refs. 52 and 53, respectively).

Several water-facility installations in the United States have assumed leadership positions in aeronautical and related hydrodynamic research in recent years. The water tunnel at NASA Ames-Dryden Flight Research Facility, modeled after the Northrop tunnel, has become a "workhorse" for NASA since its inception in the early 1980s. Considerable work has been done in cooperation with industry, universities, and other U.S. government agencies to increase the experimental data base on advanced military aircraft configurations. The Flow Research Company towing tank has most recently been used in support of the Air Force supermaneuverability program to study the unsteady aerodynamics of slender wings and bodies undergoing pitching oscillations (Refs. 54 and 55). The Tracor model basin was used to simulate the pitch-up maneuvers of a slender generic fighter model (Ref. 56).

Several other organizations have recently acquired water tunnels. NASA's Langley Research Center constructed a facility with a vertical test section similar to the NASA Ames-Dryden tunnel and is initiating a number of projects to support their aeronautics research programs. The success of the pilot water tunnel at AFWAL at Wright-Patterson Air Force Base has led to the installation of a larger ONERA-type water tunnel with a vertical 24- by 24-in. test section. This tunnel is undergoing operational checkout tests and is expected to be in use as a research facility in November 1986. Eidetics International has completed a new water tunnel/channel with a 15- by 20-in. horizontal test section incorporating a unique downstream viewing window to permit flow visualization in the cross-flow plane as well as the usual planform and side views. A larger version of the same tunnel with 24- by 36-in. test section is also under construction and is intended primarily to provide a capability for performing both static and dynamic experiments at higher angles of attack (to 90°) to support technology advancements related to fighter aircraft. A water tunnel designed by the Visual Aerodynamics Division of Eidetics International with a 24- by 24-in. test section was recently installed at the General Dynamics Corporation in Fort Worth to support their in-house research programs in advanced fighter technology.

The installations cited above have equally significant counterparts in Europe. In addition to ONERA, the Bertin and Company water tunnel in France was utilized recently to test a canard-wing arrangement for which flow-visualization, pressures, velocities, and forces were obtained (Ref. 57). Numerous installations are in operation in England and are used for diverse aerodynamic and hydrodynamic flow problems. The No. 2 Ship Tank and Rotating Arm in the Maneuvering Tank at the Admiralty Research Establishment, which has been in operation for decades, demonstrated the powerful vortex flows shed from the hull of a modern, highly maneuverable submarine model (Ref. 58). A systematic comparison of vortex positions obtained on slender missile configurations in water tunnel and wind tunnel facilities was recently made at the British Aerospace Military Aircraft Division (Ref. 59). Qualitative and quantitative testing of parachute canopies of various shape and porosity was conducted in the Southhampton (England) Towing Channel to evaluate pitch stability characteristics (Ref. 60). IMI Summerfield in England studied the internal flow characteristics of a ramrocket combustion chamber (Ref. 61), and the flow-visualization results led to an improved fuel supply design. Unsteady flow phenomena were investigated in the towing tank of DFVLR in Germany, where aircraft models underwent prescribed accelerations and decelerations (Ref. 62). The University of Stuttgart constructed two new water facilities, and recent results of research work conducted in these installations are provided in Ref. 63. Models of complete military and commercial aircraft configurations and isolated airframe components have been tested in the MBB water tunnel (Ref. 41).

Water facilities are an important element in vehicle design in Asian countries. A high-speed water tunnel (up to 10 ft/sec) designed by the Visual Aerodynamics Division of Eidetics International was installed in a research laboratory at the Aero Industry Development Center in Taiwan in 1984 to support the aircraft development programs in that country. This tunnel has a 24- by 24-in. horizontal test section. The Peking Institute in the People's Republic of China has employed a water tunnel to visualize the vortex flows about strake-wing planforms (Ref. 64). Japanese researchers have made extensive use of water facilities to understand the fluid flows about the various aerodynamic and hydrodynamic shapes. Examples of their work are provided in Ref. 9. Mitsubishi Heavy Industries employed a towing tank to study surface ship designs. A study (Ref. 65) at Mitsubishi led to the solution of a vibration problem by improved hull design obtained through systematic water facility testing.

The burgeoning applications of water facilities to the design of vehicles are apparent from the preceding historical review. The following section will discuss specific investigations in water facilities to demonstrate their role in the vehicle design process. These representative investigations will demonstrate the strengths and limitations of water facilities in aeronautical and related hydrodynamic research.

3. SPECIFIC APPLICATIONS OF WATER FACILITIES TO AERONAUTICAL AND RELATED HYDRODYNAMIC PROBLEMS

Experiments performed in the NAE, CalTech, Northrop, and NASA Ames-Dryden water facilities are described in this section to provide a flavor of the myriad applications of these installations to air, ground, and marine vehicle design. NAE and CalTech have long-standing traditions in the application of water tunnels to aeronautical and related hydrodynamic problems. The Northrop and NASA Ames-Dryden facilities represent a "new generation" of water tunnels that have made significant contributions to vehicle design. Collectively, these installations represent over 100 years of water-facility experience. Emphasis will be placed on experiments pertinent to current and future commercial and military vehicles.

3.1 National Aeronautical Establishment, Ottawa, Canada

The NAE water tunnel (Fig. 5) is a continuous-flow, closed-circuit design having a 10- by 13-in. horizontal test section. Flow velocities in the working section can vary from 0.2 to 10 ft/sec. The diverse experiments conducted in this facility encompass steady and unsteady, and attached and separated flows about air, ground, and marine vehicles. A detailed description of this installation is provided by Dobrodzicki (Ref. 23).

Figure 6 illustrates the flow about a wing with a submerged lifting fan in proximity to the ground. The fluid tracers reveal the fan efflux, recirculation region, and fountain effect. The fan-wing and jet-wing flow interactions were useful in interpreting the anomalies in the lift, drag, and pitching moment characteristics obtained in wind tunnel tests. The simulation of this flow situation is of current interest to advanced fighter aircraft configurations with a requirement for short takeoff and vertical landing (STOVL) capability. For such configurations, water flow visualization could provide insight regarding the jet-induced effects on the configuration aerodynamics and potential hot-gas reingestion problems.

Figure 7 shows the interaction of the simulated exhaust from a wing-mounted engine with a wing and slotted trailing-edge flap arrangement. This is representative of the externally blown-flap (EBF) concept that was applied to the McDonnel-Douglas YC-15 military transport configuration. The supercirculation effect induced by the high-velocity jet is clearly illustrated in the flow-visualization photograph. It is noted that the boundary-layer separation characteristics of the unpowered wing and flap combination are not accurately represented in the water tunnel owing to the subscritical Reynolds number and the subsequent laminar separation. However, the ability of the jet exhaust to reattach the flow to the wing and flap surface is qualitatively represented. At higher jet momentum, the jet-induced effects on the potential flow field are simulated in a quantitative sense.

The boundary-layer flow-separation characteristics of a military transport model are shown in Fig. 8. Results of such tests must be carefully interpreted because of the low Reynolds number conditions typical of water tunnel operation. Used judiciously, however, flow visualization can indicate regions on the aircraft surface that may be susceptible to flow separation.

A related study concerns the flow separation from the upswept rear fuselage typical of a rear-loading transport aircraft. The vortex pair shed from the aft fuselage section is shown in Fig. 9. The strength and location of the vortices will vary with the Reynolds number because of the lack of a fixed line of boundary-layer separation. Despite this, the water flow simulation was used to identify the source of degraded performance and stability problems as well as unsteady loads on cargo doors. This flow situation resembles the vortex formation on displacement hulls and submersible vehicles.

The aerodynamic cross-coupling effects associated with an oscillating generic fighter model were studied in water tunnel flow-visualization experiments. A representative result is shown in Fig. 10. The water flow simulation revealed a lateral oscillation of the forebody vortices caused by an oscillation in pitch and, as a result, the vortices were observed to shift from one side to the other of a top-mounted vertical fin. The relatively simple experiment provided a plausible flow mechanism that would lead to secondary lateral aerodynamic forces in response to a primary pitching maneuver. This study indicated that the unsteady, separated flow field about a slender configuration could be studied in a qualitative sense in a water facility despite the sensitivity of the forebody vortical motions to the Reynolds number.

The modulation of the flow-separation characteristics to improve ground vehicle performance was effectively demonstrated in the water tunnel. Figure 11 reveals a large improvement in the flow about a tractor-trailer due to the installation of a cab deflector. This modification led to reduced drag and increased stability and is now a standard "fix" on most ground transport vehicles of this class. The results from this investigation indicate that small-scale model testing in a water facility operating at low Reynolds number can yield substantial design improvements on vehicles that are Reynolds-number-sensitive and nonvortex-dominated.

3.2 California Institute of Technology, Pasadena, California

The Hydrodynamics Laboratory at CalTech consists of the Free Surface Water Tunnel (FSWT) and the High Speed Water Tunnel (HSWT). The FSWT depicted in Fig. 12 is a closed-circuit circulation system lying in a vertical plane. The horizontal test section is 20 in. wide by 30 in. deep and flow speeds up to 25 ft/sec can be obtained. The top, or free, surface is an air-water interface. This arrangement allows investigations to be performed on bodies acting on or at a prescribed distance below the water surface, such as a ventilated hydrofoil. The HSWT is also a closed-circuit design lying in a vertical plane and features interchangeable 2-D and axisymmetric working sections. The 2-D section, used principally to obtain sectional characteristics of hydrofoils, is 6 in. by 30 in. by 50 in. long, whereas the axisymmetric section is 14 in. in diameter and 46 in. long. Flow speeds up to 100 ft/sec and pressures from 100 psig to the vapor pressure of water are achievable.

In addition to flow visualization, the capabilities exist to measure steady and unsteady forces and moments and to obtain quantitative flow-field information using a laser doppler velocimeter (LDV). A detailed account of the CalTech facilities is provided by Ward (Ref. 66).

Applications of the CalTech water facilities to vehicle design have typically pertained to marine craft. The inception and scaling of cavitation on hydrodynamic shapes have been studied extensively. Studies performed in the HSWT demonstrated the importance of the boundary layer in cavitation inception. This was accomplished using a Schlieren system to visualize the origin and migration of cavitation bubbles within the boundary layer on a bluff body and their subsequent entrainment into the mainstream. A representative result from a study of cavitation phenomena is shown in Fig. 13, which depicts the cavitating flow over a 2-D wedge at high angle of attack.

Recent emphasis has been placed on the development of inlets suitable for water-jet propulsion systems. Sophisticated inlet models have been tested in the HSWT and FSWT that featured translating and rotating lips, variable-geometry walls, and auxiliary or secondary inlets. The influence of upstream air content, the thickness of the approaching boundary layer, and numerous boundary-layer control devices on the inception of cavitation and inlet recovery efficiency have been determined in these investigations.

Hydrofoil development projects have addressed the effects of flaps in cavity flow, the study of hydrofoil sections having good performance in fully wetted and cavity flow, and the performance of ventilated foils near a free surface. The latter experiment provided verification of a theory by Furuya (Ref. 67) to predict the forces on supercavitating or ventilated hydrofoils of finite aspect ratio, arbitrary shape, and variable submergence.

Aeronautical research projects pertaining to the trailing vortex systems generated by lifting surfaces were undertaken in the FSWT. The axial and tangential velocity profiles in the wake region were measured using an LDV system and the data were used to confirm a theory for the structure and decay rate of a trailing vortex.

The experiments performed in the CalTech installations exemplify the capabilities of water facilities to yield qualitative and quantitative surface and off-body flow-field information to aid in theory development and marine and flight vehicle design.

3.3 Northrop Corporation, Aircraft Division, Hawthorne, California

The Northrop Corporation water tunnel is a continuous-flow, closed-circuit facility having 16- by 24-in. vertical test section (Fig. 14). This installation has been used as a diagnostic tool to aid in the aircraft design process since its inception in 1977. It was preceded by a small pilot water tunnel having a 6- by 6-in. vertical test section that could operate in gravity discharge and continuous-flow modes.

The Northrop installations marked the advent of water facilities that were dedicated to the study of the vortex flows developed on advanced tactical/fighter aircraft operating at extreme attitudes. These installations satisfied the need for a visualization tool to improve the understanding and control of the complex vortical flows that have become characteristic of highly maneuverable military aircraft beginning with the General Dynamics YF-16 and the Northrop YF-17 lightweight fighters in the 1970s.

At a very early stage of its operation, the pilot tunnel demonstrated the utility of a water facility operating at very low speed (0.25 ft/sec) and low Reynolds number (10,000/ft) to vividly depict the vortical motion about a small-scale model of a complete fighter configuration. Figure 15 shows the vortex arising from flow separation along the sharp edge of a wing LEX on a 1/72-scale YF-17 at an angle of attack of 20°. Wortmann has commented in a recent paper (Ref. 68) that this, and similar water facility results, bear little resemblance to the real flow and are principally of public relations value. This is hardly the case, however, because this single flow-visualization photograph demonstrates several important flow-field features that have been observed in wind tunnels and in flight (Ref. 34). In addition, the interpretation of the nonlinear forces and moments and vortex-induced surface pressures is facilitated by the detailed 3-D flow visualization. For example, the development of a concentrated vortical flow above the wing surface and the favorable LEX vortex-induced effects on the wing flow-separation characteristics correlate well with the nonlinear lift increase at moderate and high angles of attack. The breakdown of the vortex core over the wing surface limits the maximum vortex-induced lift increment and can promote pitch instability. The proximity of the unburst vortical flows to suitably placed twin vertical tails enhances the stabilizer effectiveness. Under certain conditions, however, the occurrence of vortex bursting near the tail surfaces can induce a severe buffet environment leading to structural failure. The flow through the boundary-layer bleed slots at the juncture of the LEX and fuselage was observed to have an adverse effect on the LEX vortex core stability at high angles of attack, thereby reducing the maximum lift in comparison to the configuration with slots closed. Clearly, the availability of off-body flow-field trends through simple water-facility experiments is of great value in the aircraft design process.

To establish confidence in the water flow simulations, flow-visualization studies were performed in the pilot and larger-scale water tunnels of the leading-edge vortex behavior on thin, sharp-edged delta wings encompassing a wide range of the leading-edge sweep angle. The vortex positions determined from the water tunnel testing were in reasonable agreement with results obtained at higher Reynolds numbers in wind tunnels (Ref. 34). This was due to the insensitivity of the primary flow separation at the sharp leading edge to changes in the Reynolds number. The fact that theoretical methods which ignore viscous effects can reasonably predict vortex flow aerodynamics is one indication of the Reynolds number insensitivity of such phenomenon. The agreement between the vortex positions determined in the water tunnel and the wind tunnel is limited, however, because of the viscous effects near the wing surface. The upper-surface boundary-layer flow separates near the leading edge, generating a secondary vortex having a sense of rotation which is opposite to that of the primary vortex. The secondary separation line and the strength and location of the secondary vortex vary with the Reynolds number. The location of the primary vortex core will be affected by the state of the boundary layer and will be somewhat inboard and higher off the wing surface when subcritical (laminar) separation occurs.

The vortex breakdown characteristics compared favorably with similar observations made in wind tunnels and in flight, as shown in Fig. 16. This correlation indicated that under certain restrictive conditions the relative importance of inertia and viscous and pressure terms was simulated in the water tunnel. Experience suggests that the adverse pressure gradient in the external potential flow field is the dominant parameter affecting the vortex breakdown at high angles of attack. The apparent success of the inviscid Euler methods to "capture" the vortex breakdown phenomenon on this class of aerodynamic shape is based on similar reasoning (Ref. 69). Provided flow separation occurs simultaneously everywhere along a sharp leading edge, a water flow simulation is expected to provide an acceptable representation of the size and structure of the wake shed from a thin wing at a high angle of attack and, consequently, the pressure field through which a vortex core must traverse. The water tunnel photograph of Fig. 17 illustrates this flow situation on a small-scale model of an advanced fighter featuring a sharp, highly swept LEX. At a similar angle of attack, pilots of this aircraft have detected a sudden increase in the external noise intensity which is associated with the forward advance of the vortex breakdown position on either side of the canopy. Another water tunnel-to-flight correlation of a qualitative nature is shown in Fig. 18, which depicts LEX vortex breakdown on a current fighter aircraft at high angle of attack. The water tunnel model (an inexpensive, plastic model) exhibits vortex bursting over the wing panel at a location approximating the burst position on the full-scale aircraft. It is upon this premise--the dominance of the adverse pressure gradient in the external potential flow field--that water-facility vortex-breakdown results can be applied to higher-Reynolds-number phenomena in air at high angles of attack.

The water tunnel became an important element in the major aircraft programs at Northrop as a result of these preliminary investigations. The ensuing flow-visualization experiments spanning the next several years demonstrated the strengths and limitations of water-facility simulations of fighter aircraft flow

fields. Emphasis was placed on studies at high angles of attack where the phenomenological aspects of the vortex-dominated flow field were insensitive to the Reynolds number.

The F-5E, F-5F, and F-20A fighter configurations were the subject of extensive flow-visualization experiments. The water tunnel was used primarily to obtain off-body flow-field information on airframe modifications for which wind tunnel and flight test data were available. For example, the LEX planform and area modifications shown in Fig. 19 increased the maximum lift and improved the static lateral-directional stability characteristics at high angles of attack. The water tunnel testing revealed enhanced stability of the LEX vortical flow at angles of attack near maximum lift, a delay to higher angle of attack of the pronounced vortex breakdown asymmetry in sideslip, and increased dynamic pressure in the vicinity of the centerline vertical tail arising from the delayed breakdown of the windward LEX vortex.

It was determined from the flow-visualization testing of these models that faired-over engine inlets could yield misleading results regarding the vortex behavior at high angles of attack. For example, the LEX vortex breakdown characteristics indicated that influx into the side-mounted inlets at moderate to high angles of attack induced a local upwash near the LEX apex so that the effective α in this region was approximately 2° higher in comparison to the blocked-inlet case. As a consequence, all ensuing fighter models were tested with flowing inlets.

The ability to visualize the vortex-engine inlet interactions subsequently led to detailed studies of fighter configurations with top-mounted inlets. The water tunnel flow visualization, in combination with wind tunnel test results, showed that careful integration of the inlet on the fuselage to take advantage of the LEX vortex-induced sweeping action could effectively control the inlet pressure recovery and dynamic distortion at high angles of attack (Ref. 70).

The F-5 configuration was also used as a test bed to evaluate propulsive lift-enhancement concepts. A representative study featured the application of spanwise blowing to the wing upper surface to reenergize the LEX vortex at high α. At sufficiently high blowing rates, a discrete vortex from the wing leading edge was also apparent, as shown in Fig. 20. In general, it was found that the blowing momentum required in water tunnel simulations to effect a particular change in the flow field was somewhat higher than that in wind tunnel testing performed at higher Reynolds numbers. This was due to the increased blowing rates that were necessary to energize the laminar boundary layer on the wing upper surface.

Water tunnel studies confirmed that the asymmetric shedding of the vortices from the slender forebody of the F-5F at zero sideslip was responsible for the large aerodynamic asymmetries at high angles of attack that were encountered in wind tunnel and flight testing. A representative result from these studies is shown in Fig. 21. Although the primary separation along the forebody sides was sensitive to the Reynolds number, the forebody vortex asymmetry was promoted by an inviscid hydrodynamic instability associated with a crowding together of the vortices near the nose (Ref. 71). As a result, the flow mechanism was amenable to study in the water tunnel. Because of the laminar separation, however, the vortices were more widely spaced along the forebody in comparison to the case of turbulent separation. Therefore, the angle of attack for onset of the vortex asymmetry was typically a few degrees higher than the onset of aerodynamic asymmetries determined from wind tunnel and flight tests.

The ability of the F-5 "shark nose" depicted in Fig. 22 to alleviate the vortex asymmetry was demonstrated in water tunnel flow-visualization tests. The broader planform and flattened cross section near the nose increased the lateral spacing of the vortices and, therefore, reduced the susceptibility to flow-field asymmetries. Wind tunnel and flight testing of the F-5F/shark nose combination revealed a significant decrease in the aerodynamic asymmetries along with improved departure/spin resistance. Similarly, the nose shape on the reconnaissance version of the F-5F with its forward-looking oblique window (RECCE nose) was shown in water flow studies to reduce the asymmetric vortex shedding at high α.

The latter studies demonstrated the sensitivity of the vortex flows to the geometry of the forebody apex region and the ability of a water facility to visualize the flow-field changes. This led to the study of numerous other active and passive methods of asymmetric sideload alleviation in the water tunnel. These included nose strakes, helical separation trips, and normal and tangential blowing on the forebody. The flow-visualization experiments provided a rapid assessment of the ability of the flow-control devices to reduce/eliminate/reverse the body vortex asymmetry. The devices that were identified as promising flow modulators in the water tunnel proved effective in controlling the β-zero asymmetries in wind tunnel testing of subscale F-5 models.

The water tunnel was a useful tool in analyzing the directional stability trends obtained in wind tunnels and in flight since at high angles of attack the forebody can strongly affect the static directional stability. An example includes the F-5F forebody, which develops an unusual vortex orientation in sideslip as shown in Fig. 23. On the basis of water tunnel/wind tunnel/flight correlations, the forebody vortices and their unique orientation were identified as the primary source of static directional stability at high angles of attack. As a consequence, the effect of forebody modifications on the yaw stability could generally be surmised from water tunnel testing by observing any changes to the forebody vortex structure and location.

The water tunnel testing of the F-5 and related fighter models revealed several limitations to the water facility simulations. At low angles of attack, generally less than 10°, the vortex core in a water tunnel is influenced by the wake region produced by laminar separation from the rear portion of the wing. As shown in Figs. 24 and 25, this alters the vortex path and also produces premature dissipation of

the vortex because of entrainment of turbulent fluid from the separated wake. In contrast, observations of the vortex behavior in wind tunnels and in flight at similar angles of attack indicated that the vortex does not burst over the wing (see Fig. 25). Rather, the discrete vortex core exhibits a trajectory that conforms closely to the curvature of the wing, particularly when leading- and trailing-edge flaps are deflected, and can interact with downstream airframe components. For similar reasons, the laminar boundary-layer separation at the subcritical conditions in the water tunnel masks the quantitative effects of deflected leading- and trailing-edge devices on the vortex stability. The simulation of the vortex behavior on wings with thickness, camber, twist, and/or leading-edge bluntness is also inadequate at low-α conditions. Investigations of these configurations, therefore, are limited to high angles of attack where flow separation occurs everywhere along the wing leading edge. Under such conditions, the fundamental character of the vortex-dominated flow is similar to that observed at higher Reynolds number. This was the justification for water tunnel studies of the Space Shuttle Orbiter by Lorincz (Ref. 72).

The scale of the vortical motions relative to the boundary-layer thickness will determine the degree to which the water-facility results can be extrapolated to higher Reynolds number. The vortices generated from wing leading-edge snags and lower and upper surface fences, for example, generally proved difficult to simulate in the water tunnel because of the strong interaction between the separated wing boundary layer and the vortical motions. An attempt to represent the interaction of the vortex generated from the nacelle strake, or engine "ear," of a commercial transport model with the wing upper surface proved futile. In flight, however, the strake vortex observed under conditions of natural condensation traversed the wing upper surface and closely followed the curvature of the wing without breakdown.

A major contribution of the water tunnel pertained to the visualization of multiple vortex flows, vortex interactions, and breakdown on fighter aircraft featuring relatively large LEXes in proximity to the forebody. Such configurations were shown to develop strong flow interactions throughout the extended angle-of-attack range owing to the persistence of the vortical motions and their proximity to one another. An example of the strong coupling of forebody and LEX vortices on a small-scale model of the F-18 is shown in Fig. 26. The flow field is characterized by symmetric forebody vortex shedding at zero sideslip and the entrainment of this vortex pair by the dominant LEX vortical flows. This multiple vortex interaction was very sensitive to small changes in the sideslip angle. Furthermore, modulation of the forebody vortex orientation in sideslip was found, under certain conditions, to influence the wing stall behavior and, hence, the lateral stability characteristics (Ref. 73). For example, the forebody vortices were resistant to asymmetric orientation in sideslip when radome strakes were installed at 40° above the maximum half-breadth. At small sideslip angles, the body vortex system was actually biased toward the windward side of the aircraft. This flow situation was unsteady, however, as the leeward body vortex would periodically pass underneath the windward vortical flow. The strake effects on the forebody-LEX vortex interactions resulted in powerful vortex-induced downwash and sidewash on the windward wing panel, thereby delaying complete wing stall to angles of attack greater than 40°. This effect was also observed in wind tunnel smoke-flow visualization. The increased roll stability arising from the strake installation was confirmed in subscale wind tunnel and full-scale flight testing. In addition, the wind tunnel model installed on a free-to-roll rig and the full-scale vehicle in flight revealed modest strake-induced lateral oscillations, or wing rock, which was consistent with the unsteady forebody-LEX vortex interactions observed in the water tunnel and wind tunnel flow-visualizations. The investigations demonstrated how changes to the forebody flow could be amplified downstream to affect the wing aerodynamics and how the understanding of complicated flow interactions could be improved through water tunnel experiments.

The simulation of multiple vortex interactions was extended to canard-wing fighter configurations. At the higher angles of attack, the water tunnel provided useful flow-field results regarding the effects of the canard downwash on the wing flow field. For example, the delay of leading-edge flow separation on the wing, the progressive development of the wing vortex with increased angle of attack, and the enhancement of the latter at high α in the presence of the canard downwash field were demonstrated in water flow experiments. The flow-visualization photograph of Fig. 27 shows a discrete wing vortex on a small-scale model of the Swedish Viggen aircraft at $\alpha = 30°$, which is well beyond the angle of attack for stall of the isolated wing.

The lateral sensitivity at high angles of attack associated with asymmetric vortex breakdown in sideslip is an inherent characteristic of any fighter aircraft employing large amounts of vortex lift. Flow-visualization investigations were conducted to improve the flow situation depicted in Fig. 28 by suitable modifications to the LEX planform and addition of LEX fences and slots to modulate the vortex core breakdown behavior in sideslip. Excellent correlations were obtained between the flow-field observations and low-speed wind tunnel data trends.

The occurrence of wing rock is common to slender-wing aircraft at high angles of attack. Water tunnel studies of a slender hypersonic research configuration unconstrained in roll revealed a self-induced, bounded lateral oscillation similar to that observed in the wind tunnel. The visualization of the oscillatory leading-edge vortex core and breakdown phenomena provided insight into possible triggering and sustaining mechanisms of this single-degree-of-freedom oscillation.

Water tunnel tests were performed on a 2-D ejector nozzle to study the effects of swirl on the exhaust plume characteristics. The flow-visualization experiments indicated that swirl dramatically reduced the primary nozzle potential core and, hence, the mixing shroud length as shown in Fig. 29. The results, which confirmed a theory developed by Chu (Ref. 74), were useful for such applications as jet noise reduction.

Another application of the water tunnel to a nonvortex-dominated flow field pertained to thrust reversers on an advanced fighter configuration in and out of ground proximity. A representative result from these experiments is shown in Fig. 30. The reverser plume shape and trajectory were observed for ranges of the nozzle geometry, orientation, and jet velocity ratio. Emphasis was placed on the jet blockage and entrainment effects on the vertical and horizontal stabilizer flow fields. It was difficult to identify the pertinent flow mechanisms, however, and the correlations with tail loads information obtained in wind tunnel tests were necessarily limited.

3.4 NASA Ames Research Center, Dryden Flight Research Facility, Edwards, California

The NASA Ames-Dryden Flow Visualization System (FVS) (Fig. 31) is a single-return facility with a 16- by 24-in. vertical test section. This installation, modeled after the Northrop water tunnel, has been in operation since 1983. The NASA facility has been used almost exclusively for the visualization and measurement of the separated flow fields about advanced military aircraft configurations. In addition to NASA in-house research, numerous cooperative ventures have been undertaken with industry, universities, and other government agencies. The NASA facility has expanded on the Northrop tunnel capabilities by developing laser-enhanced visualization (LEV) and 2-D laser velocimeter (LV) techniques for the water flow studies. In addition, successful attempts have been made to obtain quantitative information using instrumented models.

Many of the flow-visualization studies have been made in support of the NASA High-Alpha Technology Program. Flow-field information has been obtained on small-scale models of the F/A-18, as shown in Fig. 32, to identify effective passive and active vortex flow-control concepts for future wind tunnel and flight testing.

A related study sponsored by the Navy featured quantitative measurements of the F/A-18 twin vertical tail buffet characteristics in the presence of LEX vortex breakdown. The water tunnel investigation, in combination with existing wind tunnel and flight test data, provided an improved understanding of vortex-empennage interactions at high angles of attack that can lead to severe tail buffeting. The surface hot-film anemometer results showed high turbulence activity on the fins at conditions coincident with vortex bursting observed from flow visualization. The vortex frequencies, vortex bursting, and dominant frequencies from the water tunnel tests correlated well with wind tunnel tests at higher Reynolds number (Ref. 75).

A generic study (Ref. 48) was made of a concept to improve the vertical-tail buffet environment. This test featured the generation of a "free vortex" with an imposed downstream pressure gradient to promote core bursting. Blowing along the core was then initiated to delay the onset of bursting. LV measurements showed that the active flow control significantly reduced the turbulence intensity. It can be inferred from these preliminary results that core blowing applied to the F/A-18 configuration would have a favorable effect on the vortex-empennage interactions at high angles of attack.

A qualitative study was made of an F/A-18 model undergoing pitch oscillations and ramp-type motions to evaluate potential dynamic lift benefits at angles of attack beyond the static maximum lift. The flow visualization revealed a lag in the flow-field response to the aircraft motion and a delay of the LEX vortex bursting in comparison to the static case. The latter phenomenon was very transient, however, as the flow field rapidly assumed its steady-state condition upon termination of the maneuver. In contrast to the results obtained at NAE on a slender generic fighter model, there was no significant lateral oscillation of the vortex flows due to the pitching maneuver. This was attributed to the dominance of the LEX vortices which emanated from fixed lines of separation and therefore were resistant to large lateral excursions.

The Space Shuttle Orbiter configuration was tested to evaluate the vortex-shedding patterns on the thick cranked wing at high angles of attack. A representative result is shown in Fig. 33. This model was used to develop a LEV capability (Ref. 49) and the resultant technique was then applied to several other configurations, including a powered AV-8A Harrier model in ground proximity and a drag-reduction concept featuring a trailing disk behind the base of a cylinder. A typical flow visualization in a streamwise plane from the latter study is shown in Fig. 34.

Other aircraft configurations that have been studied in the NASA installation include the McDonnell-Douglas F-15 and F-4, the Grumman/DARPA X-29, the General Dynamics F-16XL, and the NASA/General Dynamics F-106 with vortex flaps. The vortex flow behavior on the NASA/LTV/Rockwell F-8 oblique wing test aircraft configuration was visualized as shown in Fig. 35. Of particular interest was the asymmetric vortex formation and breakdown on this skewed wing arrangement and the interaction of the vortical flows with the vertical tail. The understanding and control of these phenomena are essential in order to obtain acceptable levels of static lateral-directional stability at moderate and high angles of attack.

In addition to experiments on specific aircraft configurations, basic aerodynamic research programs have also been supported by water tunnel experiments in the NASA Ames-Dryden facility. One example is a recent study (Ref. 76) performed by Eidetics International for the Air Force to investigate methods of vortex control to enhance aerodynamic control on fighter aircraft at high attitudes. The aim of this flow-visualization study was to explore methods of altering the natural state of the forebody and LEX vortices by interjecting into the flow field either small surfaces or blowing jets.

4. SUMMARY

A review has been made of the role of water facilities in vehicle design. The use of water as a flow-visualization medium began very early. The scientific application of water flow visualization began in the 15th century with the observations and sketches of Leonardo da Vinci, who also designed the first water tunnel. Leonardo hypothesized that flows in water and air were similar, which was of great importance to the advancement of fluid mechanics.

In the centuries to follow, sporadic experiments on simple shapes were performed in water, primarily for marine craft applications. The pioneering research of Ludwig Prandtl and his colleagues and the dawning of the era of flight in the early 20th century marked an upsurge in the use of water facilities for vehicle design. In the ensuing decades up through World War II, water tunnels, channels, and towing tanks yielded useful qualitative, and sometimes quantitative, information on various aerodynamic and hydrodynamic shapes suitable for flight and marine vehicles.

The trend toward increased vehicle size and speed posed a scaling problem for water facility simulations. The matching of the Froude number in marine craft testing was generally at the expense of a large Reynolds number gap. The scaling of cavitation phenomena was a continual challenge. Water flow simulations were necessarily restricted to the incompressible flow regime and could not represent the phenomena encountered on high-speed aircraft that emerged during World War II. A significant Reynolds number mismatch was also present in the testing of flight vehicles in water facilities. These problems continue to the present day.

The utilization of controlled flow separations and vortex flows by design to improve vehicle performance emerged in the 1950s. This increased the utility of water facilities as a vehicle design tool largely because the fundamental structure of these flows was insensitive to the Reynolds number. The rapid advancement of vehicle technology since that time has resulted in expanded operating envelopes and corresponding increase in the flow-field complexity. Water facility applications and capabilities have kept pace with these technology developments and these installations have assumed a prominent role in the design of air, ground, and marine vehicles. Water tunnel, channel, and towing-tank facilities are in operation in several countries around the world, providing detailed flow-field information that will assist in solving myriad present and future aeronautical and related hydrodynamic problems.

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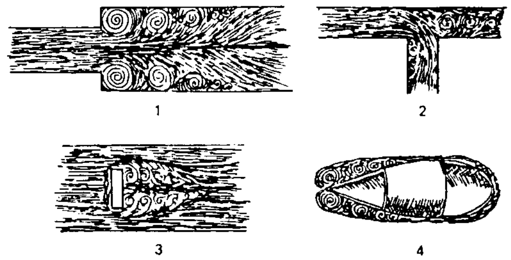


Figure 1. Fluid flow sketches by Leonardo da Vinci (from Ref. 1).

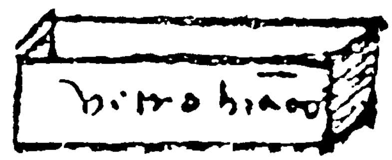
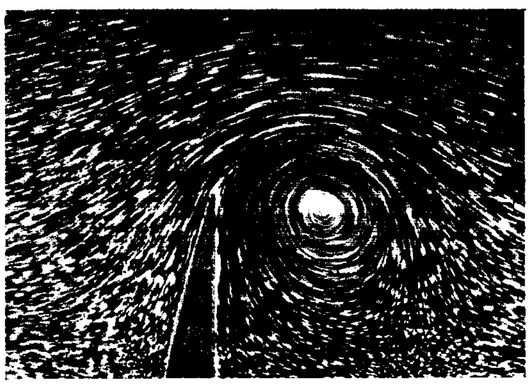
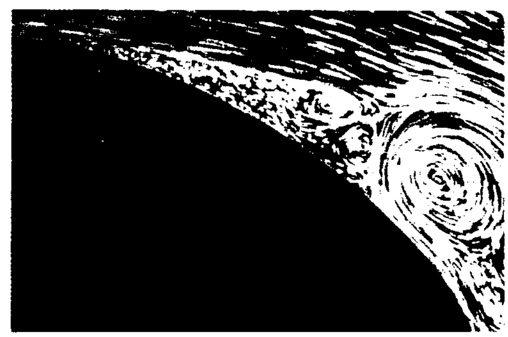


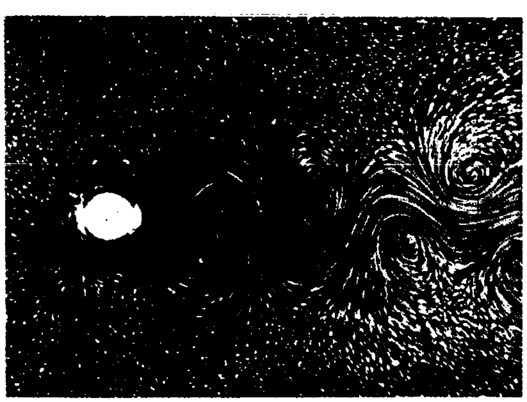
Figure 2. The box with the inscription "white glass," read from right to left as was Leonardo's habit, represents the first historic example of a water tunnel (from Ref. 5).



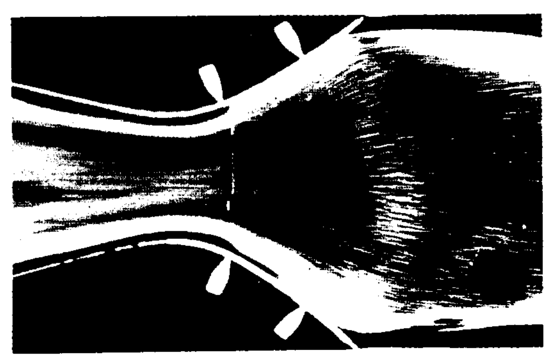
(a) Flow past a knife edge.



(b) Flow along aft portion of blunt body.

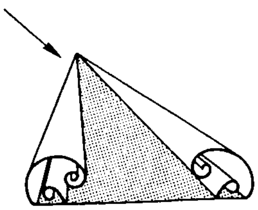


(c) Kármán vortex street downstream of cylinder.

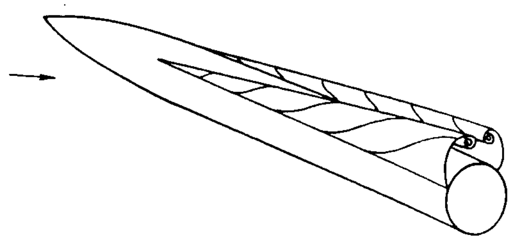


(d) Flow in a sharply diverging channel with wall suction.

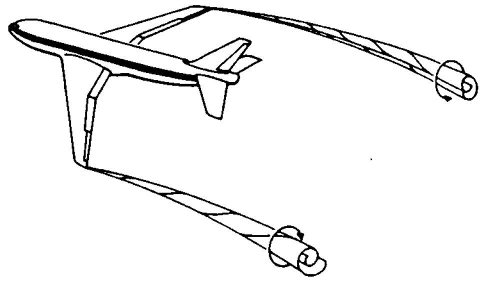
Figure 3. Representative water flow-visualization results of Prandtl (from Ref. 12).



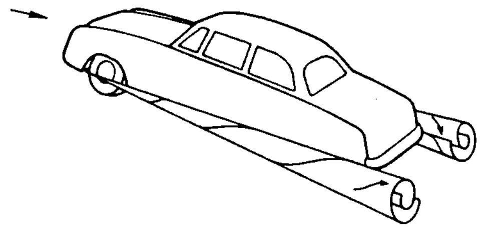
(a) Leading-edge vortex on a slender wing.



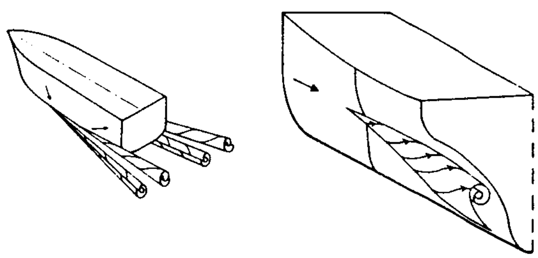
(b) Vortices on the lee side of a missile.



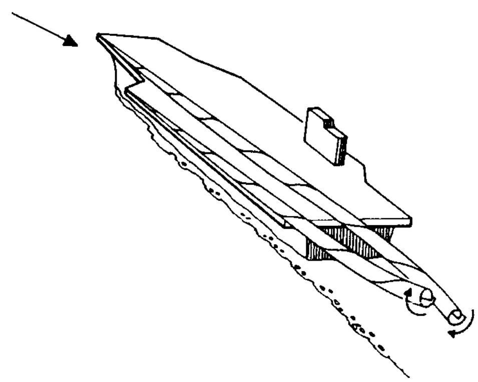
(c) Wingtip vortices on a commercial transport aircraft.



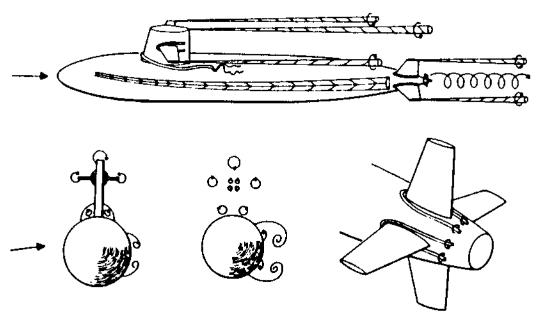
(d) Side-edge vortices on an automobile.



(e) Bilge and stern vortices on displacement hulls.



(f) Vortex flows on an aircraft carrier flight deck.



(g) Vortex flows about a maneuvering submarine.

Figure 4. Sketches of vortex flows shed from air, ground, and marine vehicles (from Ref. 1).

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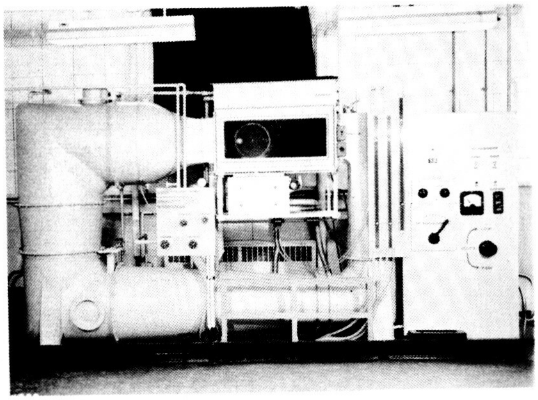


Figure 5. NAE water tunnel.

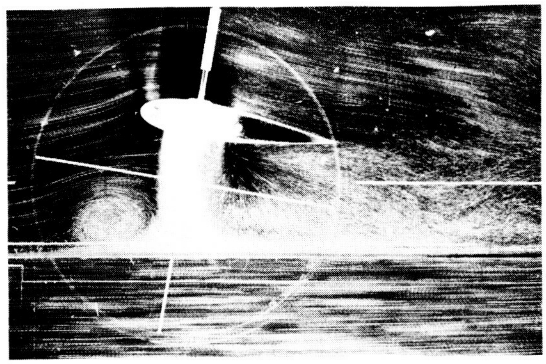


Figure 6. Wing-submerged lifting fan (NAE water tunnel).

Figure 7. EBF arrangement (NAE water tunnel).

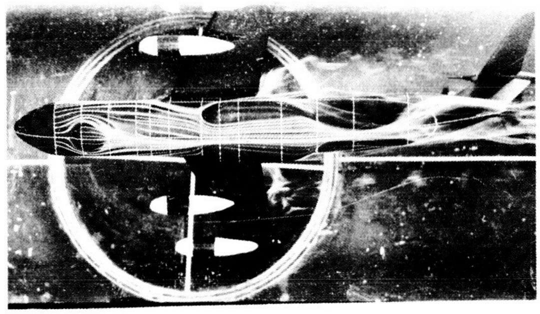


Figure 8. Surface flow on a C-5 transport model (NAE water tunnel).

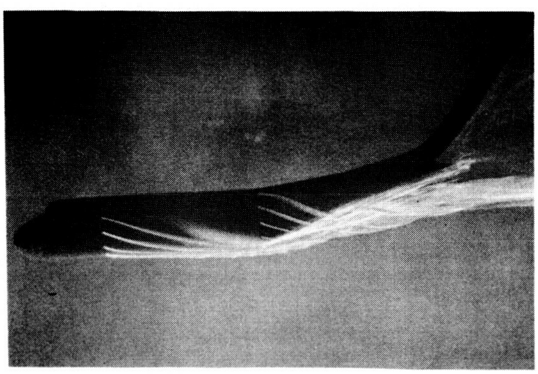


Figure 9. Vortex wake of lifting fuselage, side view (NAE water tunnel).

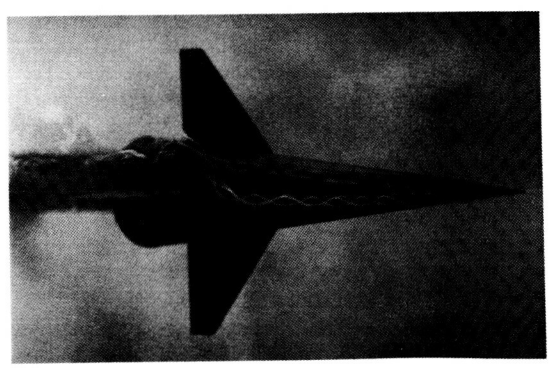
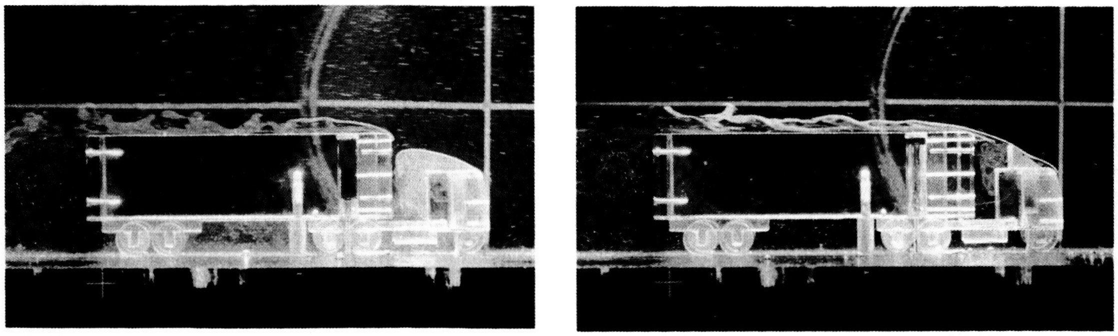


Figure 10. Modern aircraft with long forebody--angle of attack 45°--vortices asymmetrical (NAE water tunnel).



(a) Original version.

(b) With deflector on cab.

Figure 11. Truck trailer (NAE water tunnel).

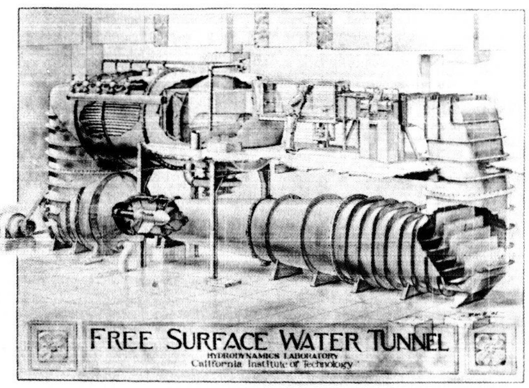


Figure 12. Sketch of the CalTech FSWT.

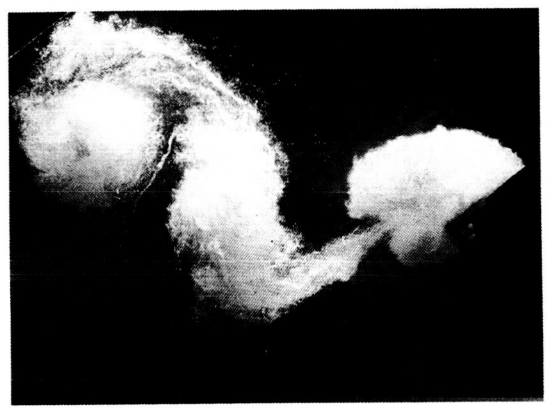


Figure 13. Cavitating flow about 2-D wedge at high angle of attack (CalTech FSWT).

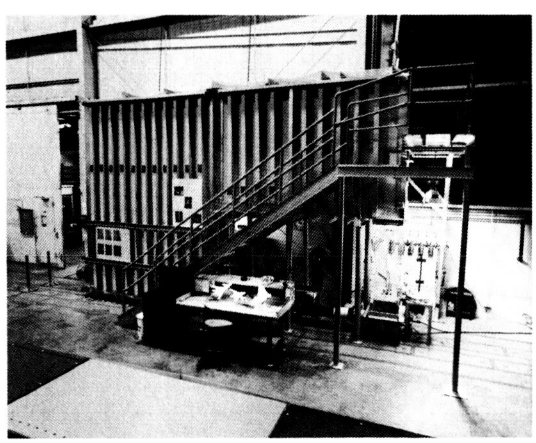


Figure 14. Northrop Corporation water tunnel.

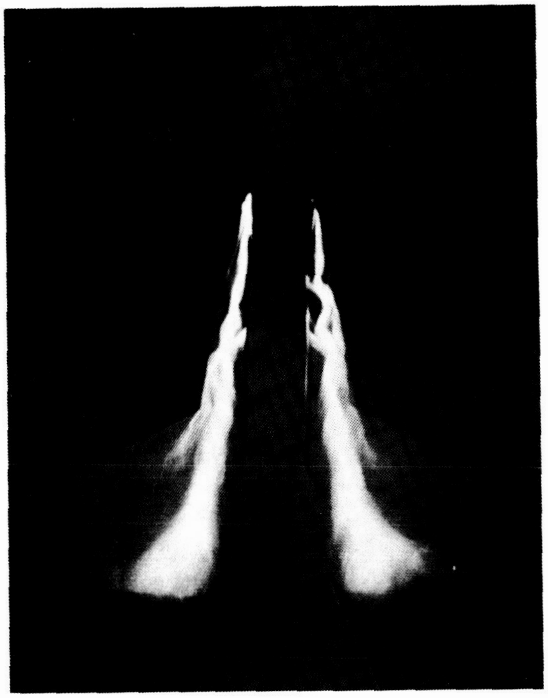


Figure 15. Vortex flows about YF-17 model at α = 20° (Northrop water tunnel).

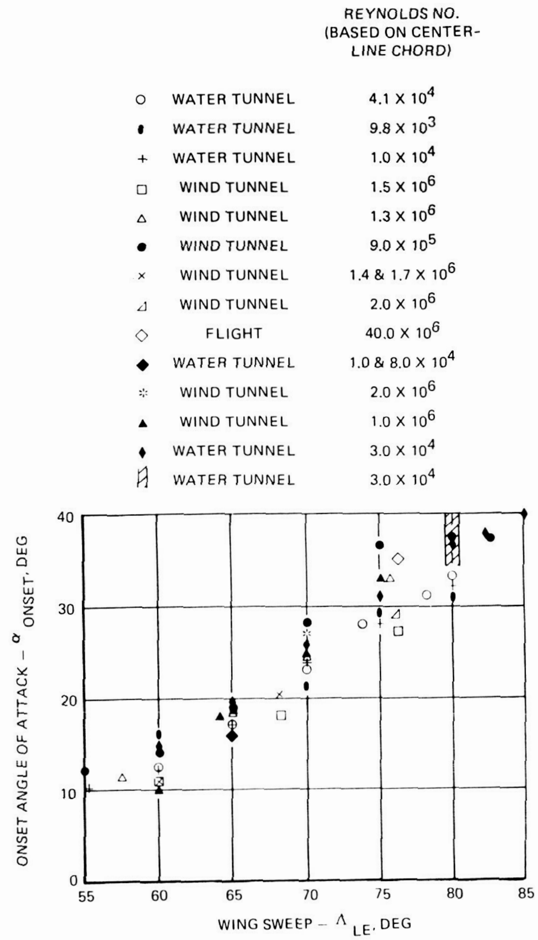
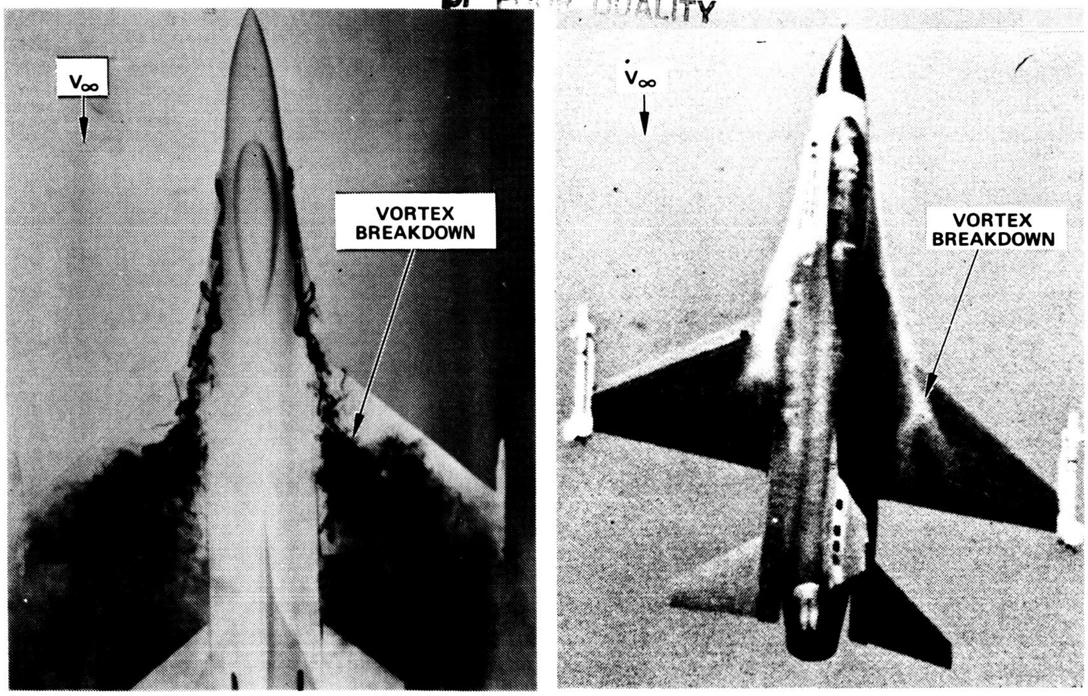


Figure 16. Effects of wing sweep and Reynolds number on delta wing vortex breakdown at the trailing edge (from Ref. 34).

Figure 17. Vortex breakdown on a small-scale model of an advanced fighter configuration (Northrop water tunnel).



(a) Northrop water tunnel--dye injection. (b) Flight--natural condensation.

Figure 18. Correlation of vortex breakdown on a current fighter aircraft at high angle of attack.

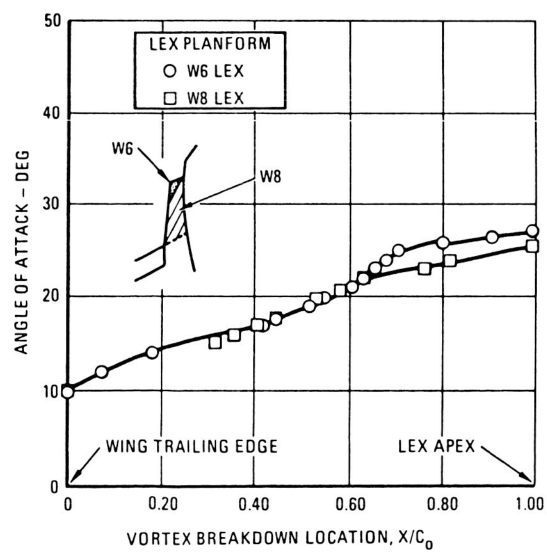
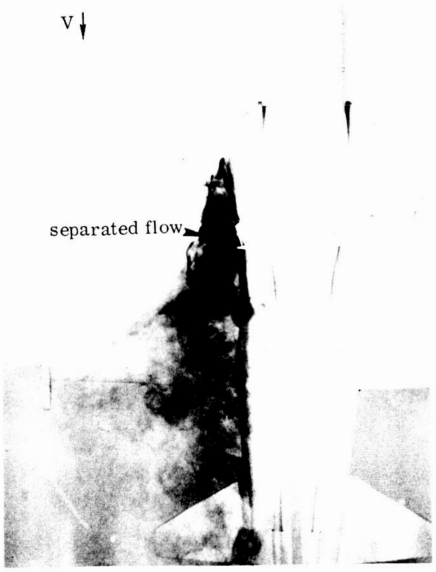
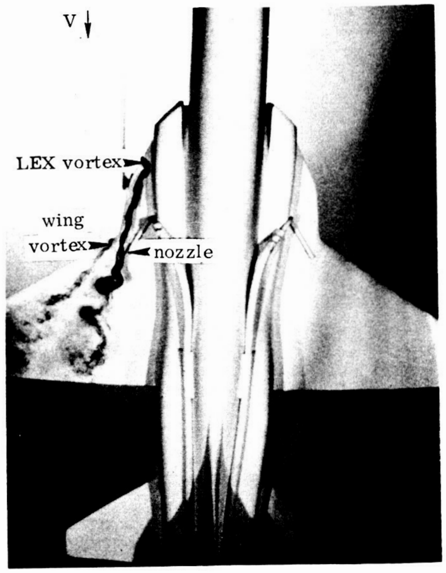


Figure 19. Effect of LEX planform modification on the progression of vortex bursting with the angle of attack (from Ref. 34).



(a) Blowing off.



(b) Blowing on.

Figure 20. Effect of wing upper surface spanwise blowing on the leading-edge vortex behavior at $\alpha = 24°$ (Northrop water tunnel).

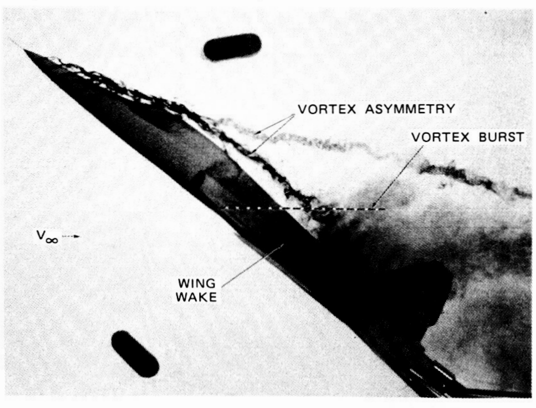


Figure 21. Asymmetric forebody vortex shedding at zero sideslip (Northrop water tunnel).

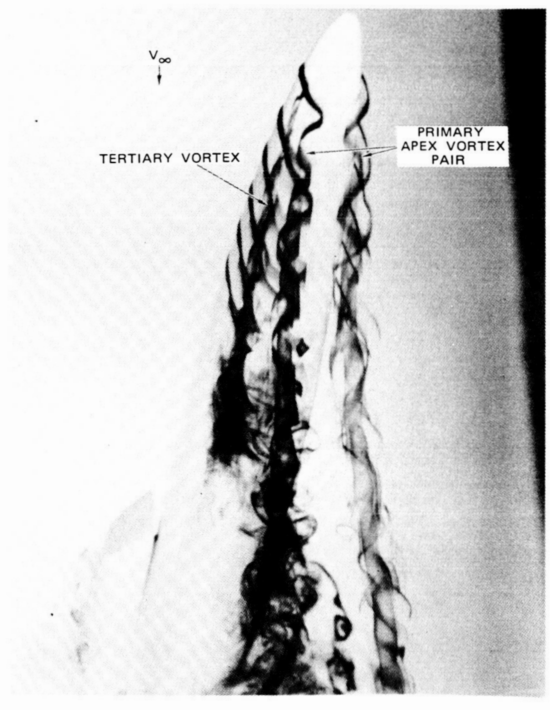


Figure 22. Close-up of vortex flows developed on forebody with shark nose (Northrop water tunnel).

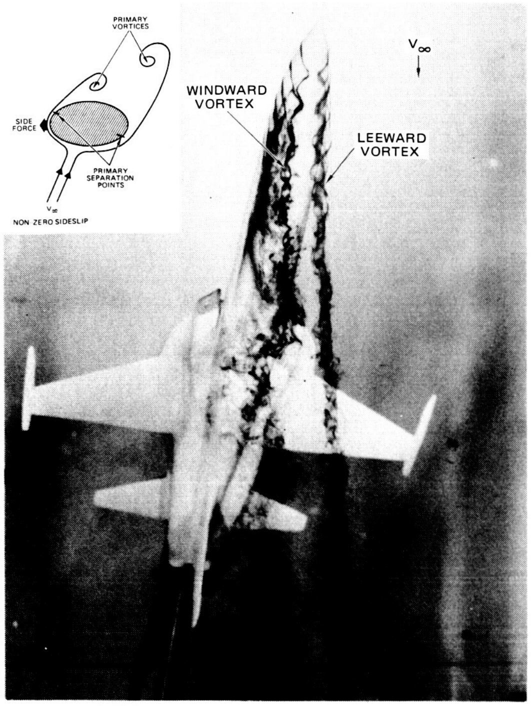


Figure 23. Forebody vortex orientation in sideslip (Northrop water tunnel).

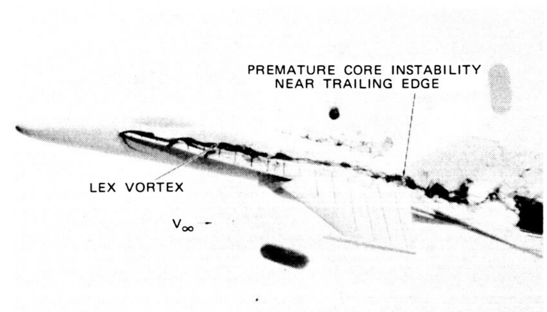


Figure 24. Vortex flow at low angle of attack (Northrop water tunnel).

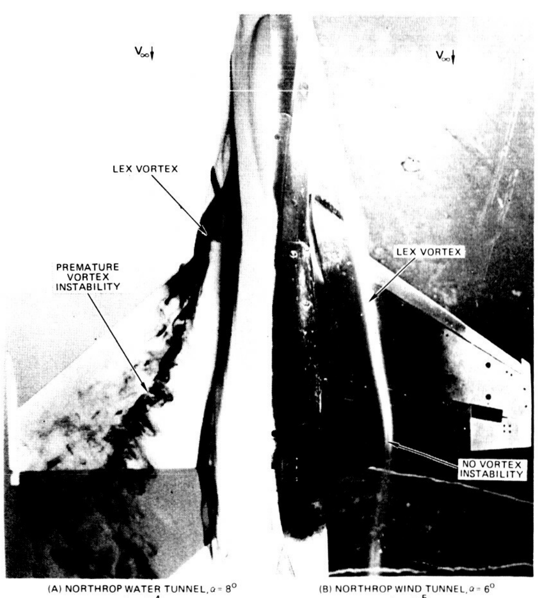


Figure 25. Comparison of vortex flow behavior in water and wind tunnel facilities (Northrop).

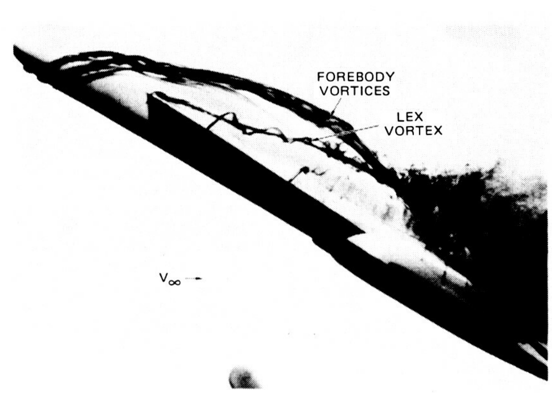


Figure 26. Forebody-wing vortex flow interactions on an advanced fighter model (Northrop water tunnel).

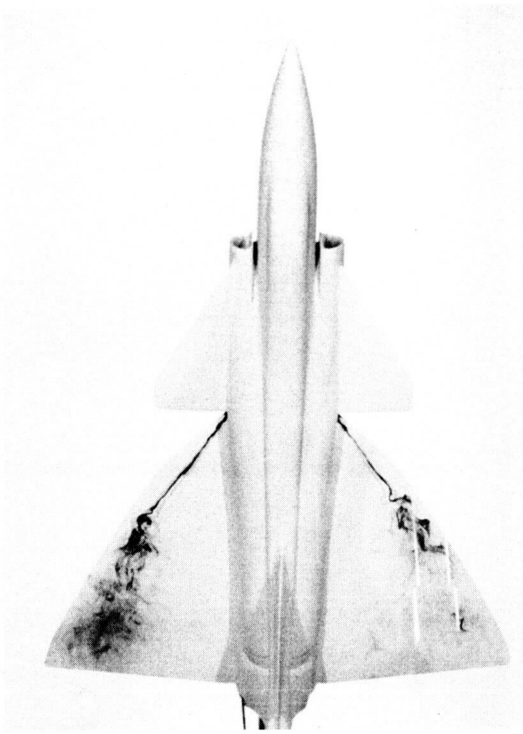


Figure 27. Vortex flows on a canard-wing fighter model (Northrop water tunnel).

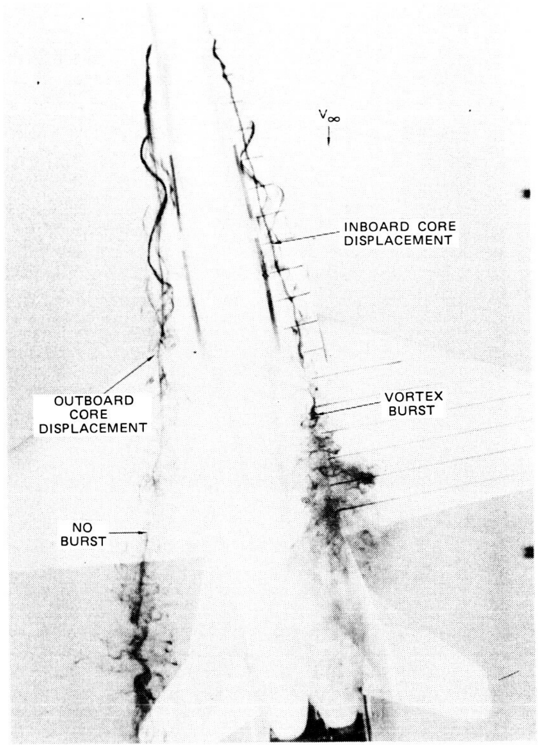


Figure 28. Asymmetric vortex breakdown in sideslip (Northrop water tunnel).

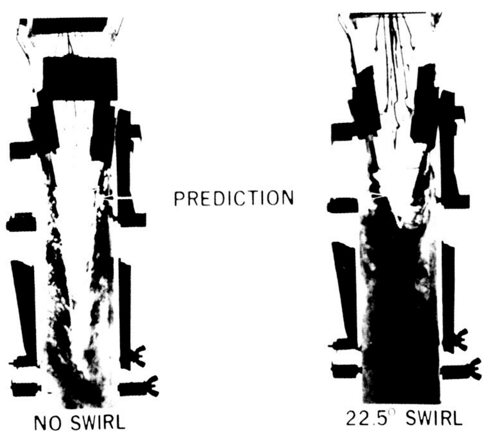


Figure 29. Effect of swirl on 2-D ejector nozzle flow (Northrop water tunnel).

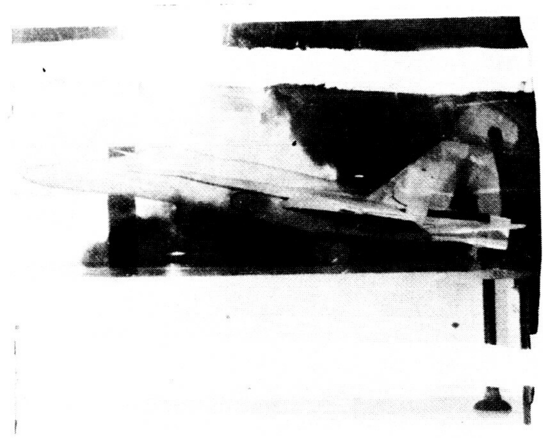


Figure 30. Thrust-reverser effect in ground proximity (Northrop water tunnel).

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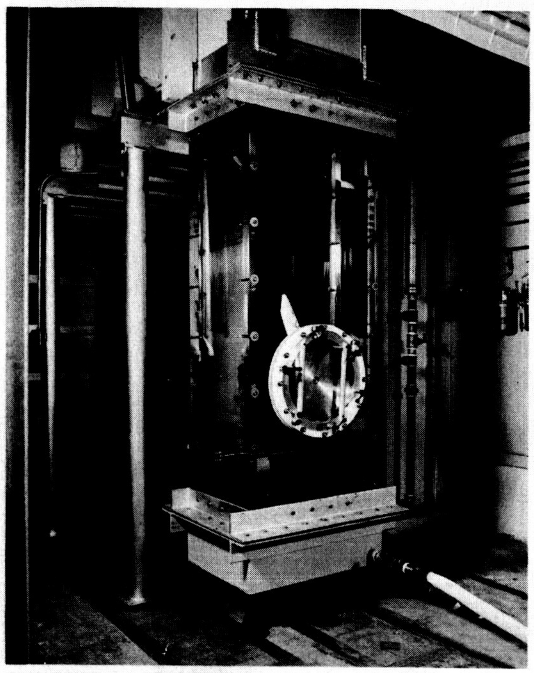


Figure 31. NASA Ames-Dryden FVS.

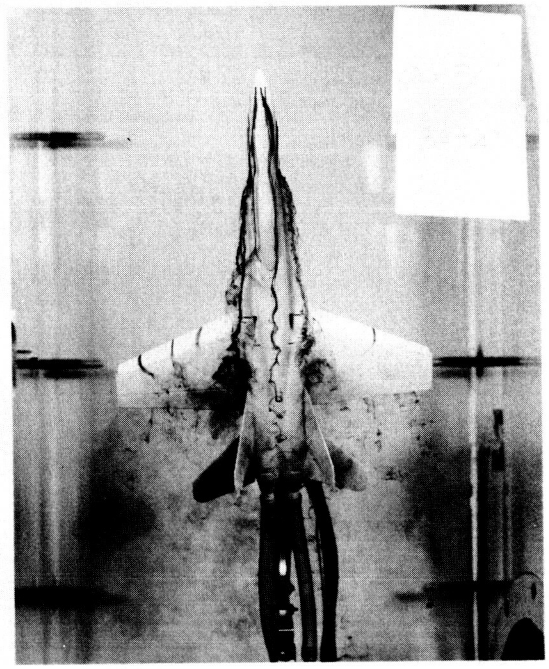


Figure 32. Vortex flows about a small-scale model of the F/A-18 (NASA Ames-Dryden water tunnel).

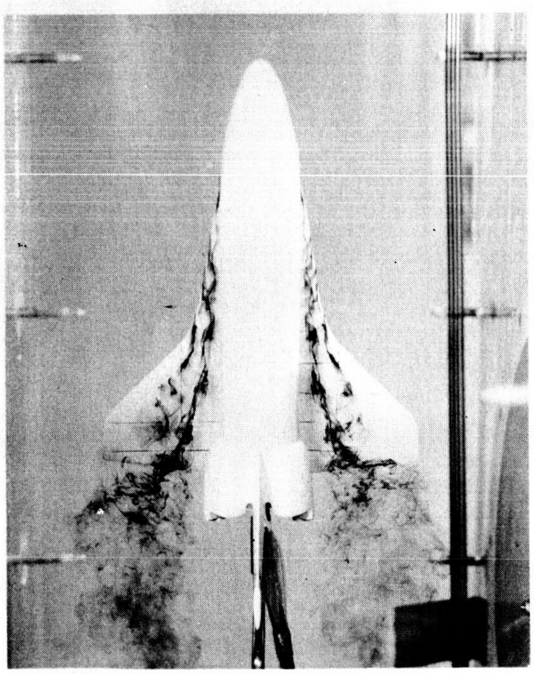


Figure 33. Vortex flows about a small-scale model of the Space Shuttle Orbiter (NASA Ames-Dryden water tunnel).

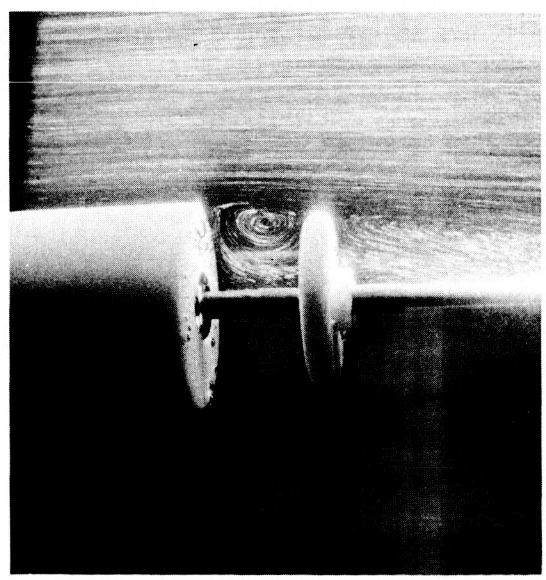
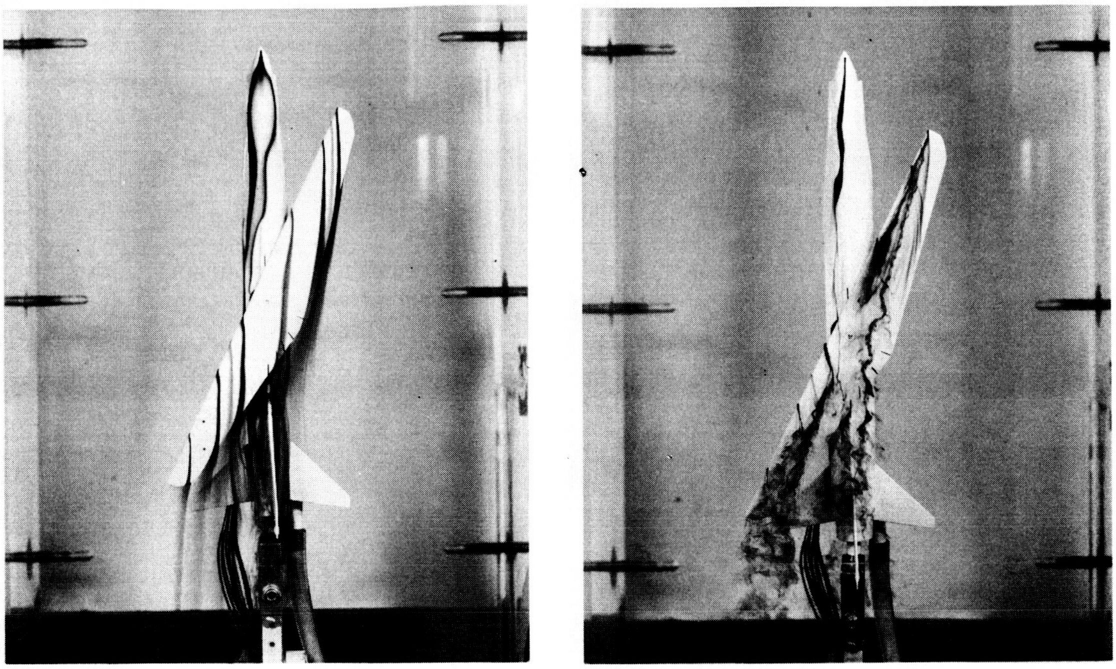


Figure 34. Laser-enhanced visualization of the flow about a cylinder with trailing disk (NASA Ames-Dryden water tunnel).



(a) Low angle of attack. (b) High angle of attack.

Figure 35. Flow visualization of a small-scale model of the F-8 oblique wing aircraft configuration (NASA Ames-Dryden water tunnel).

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15. Supplementary Notes

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16. Abstract

Water facilities play a fundamental role in the design of air, ground, and marine vehicles by providing a qualitative, and sometimes quantitative, description of complex flow phenomena. Water tunnels, channels, and tow tanks used as flow-diagnostic tools have experienced a renaissance in recent years in response to the increased complexity of designs suitable for advanced technology vehicles. These vehicles are frequently characterized by large regions of steady and unsteady three-dimensional flow separation and ensuing vortical flows. The visualization and interpretation of the complicated fluid motions about isolated vehicle components and complete configurations in a time- and cost-effective manner in hydrodynamic test facilities is a key element in the development of flow control concepts and, hence, improved vehicle designs.

This paper presents a historical perspective of the role of water facilities in the vehicle design process. The application of water facilities to specific aerodynamic and hydrodynamic flow problems is discussed, and the strengths and limitations of these important experimental tools are emphasized.

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